Programming at Fast Scale: Consistency + Lock Freedom

cs378h

Today

Questions?

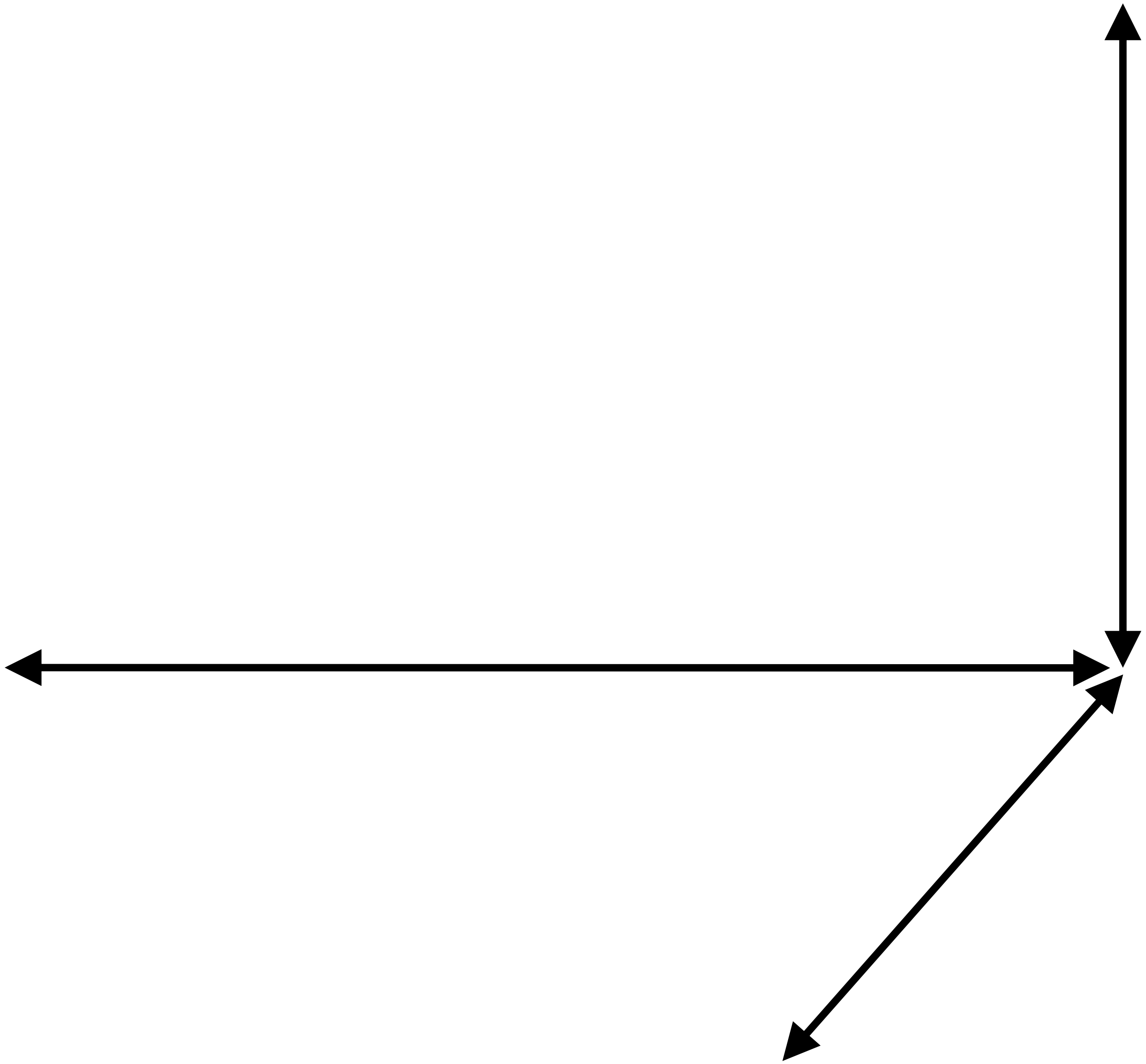
Administrivia

- Project Proposal Due Today!

Agenda:

- Consistency
- Lock Freedom

Review: Another Framework



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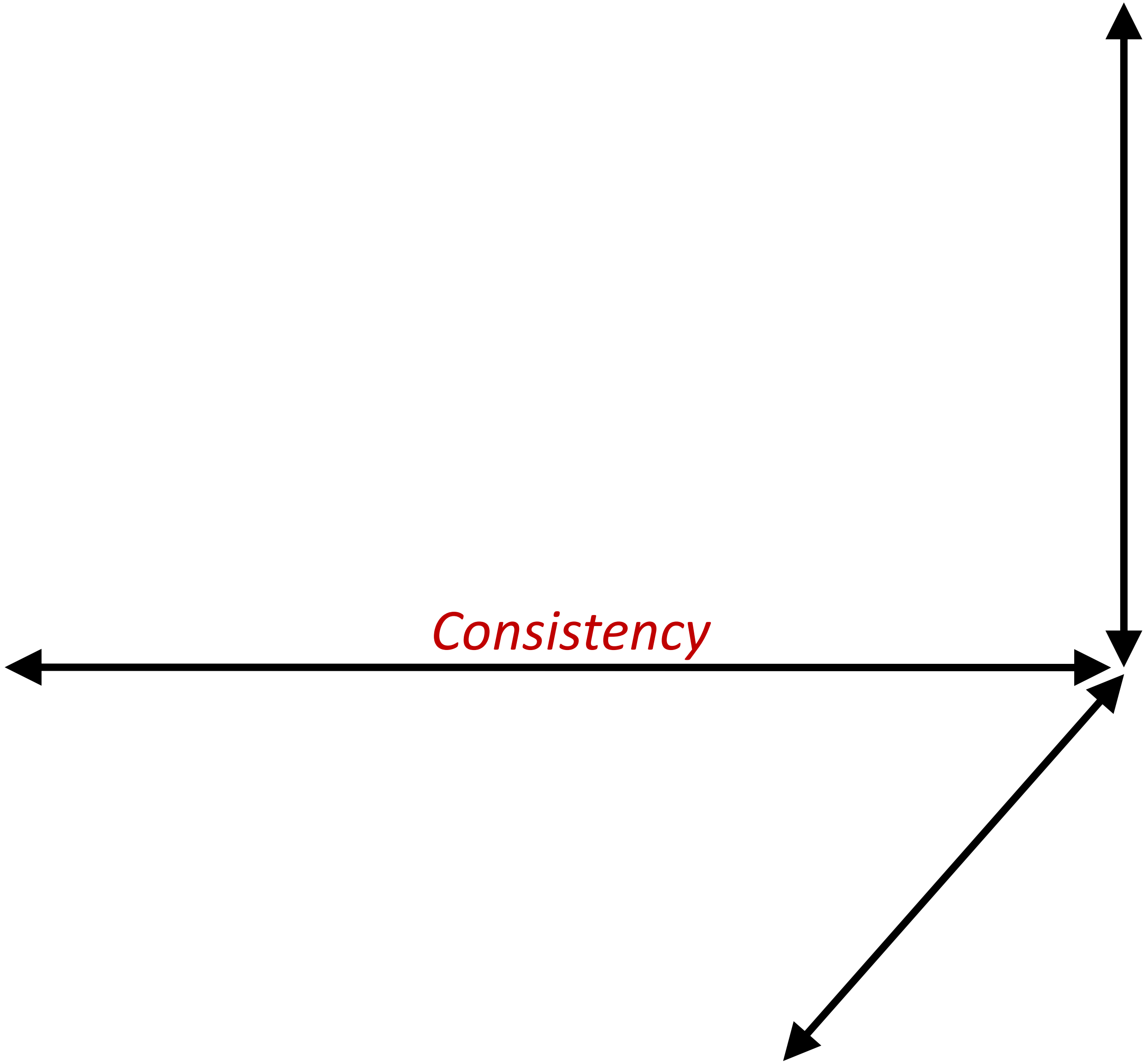

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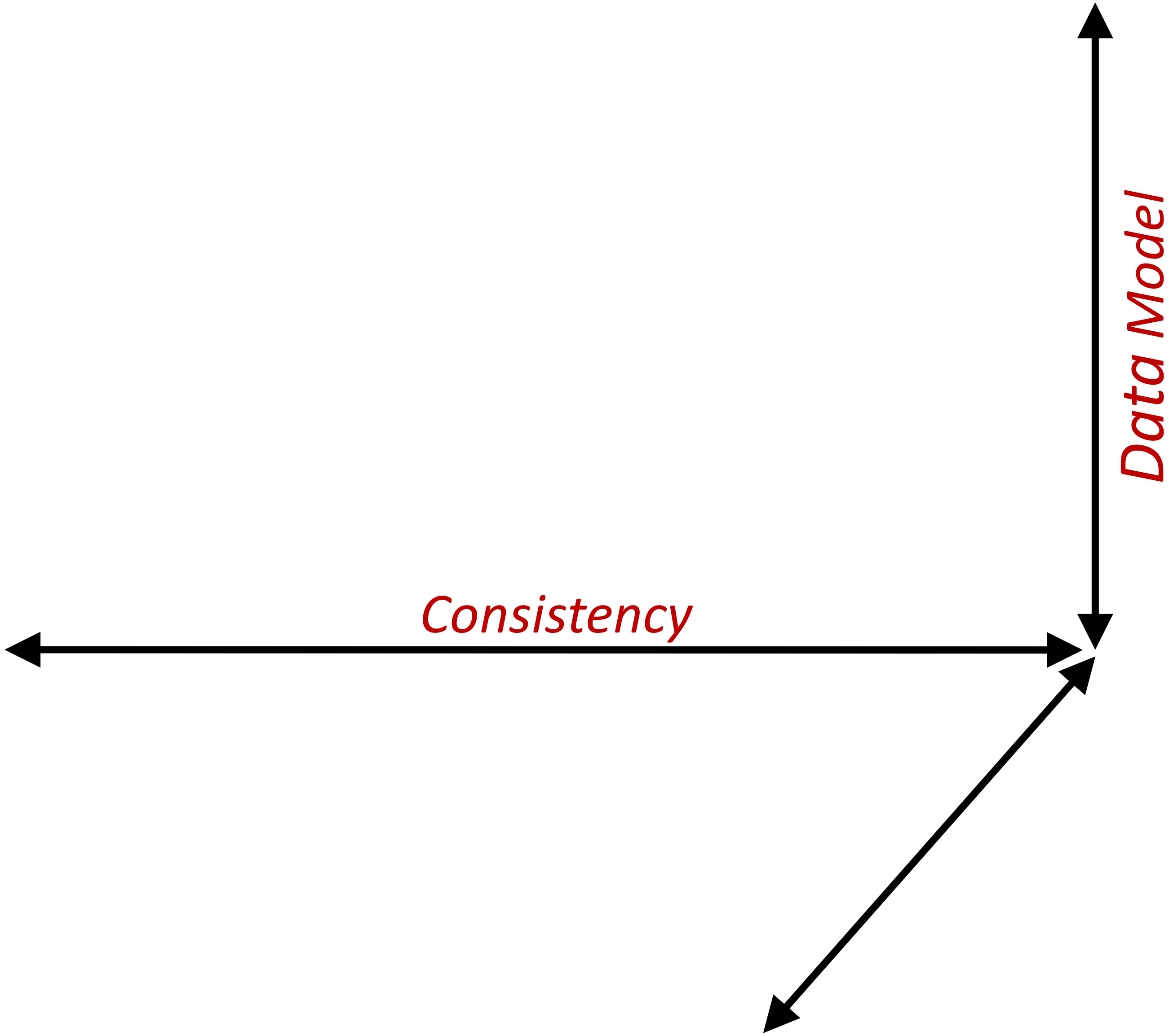

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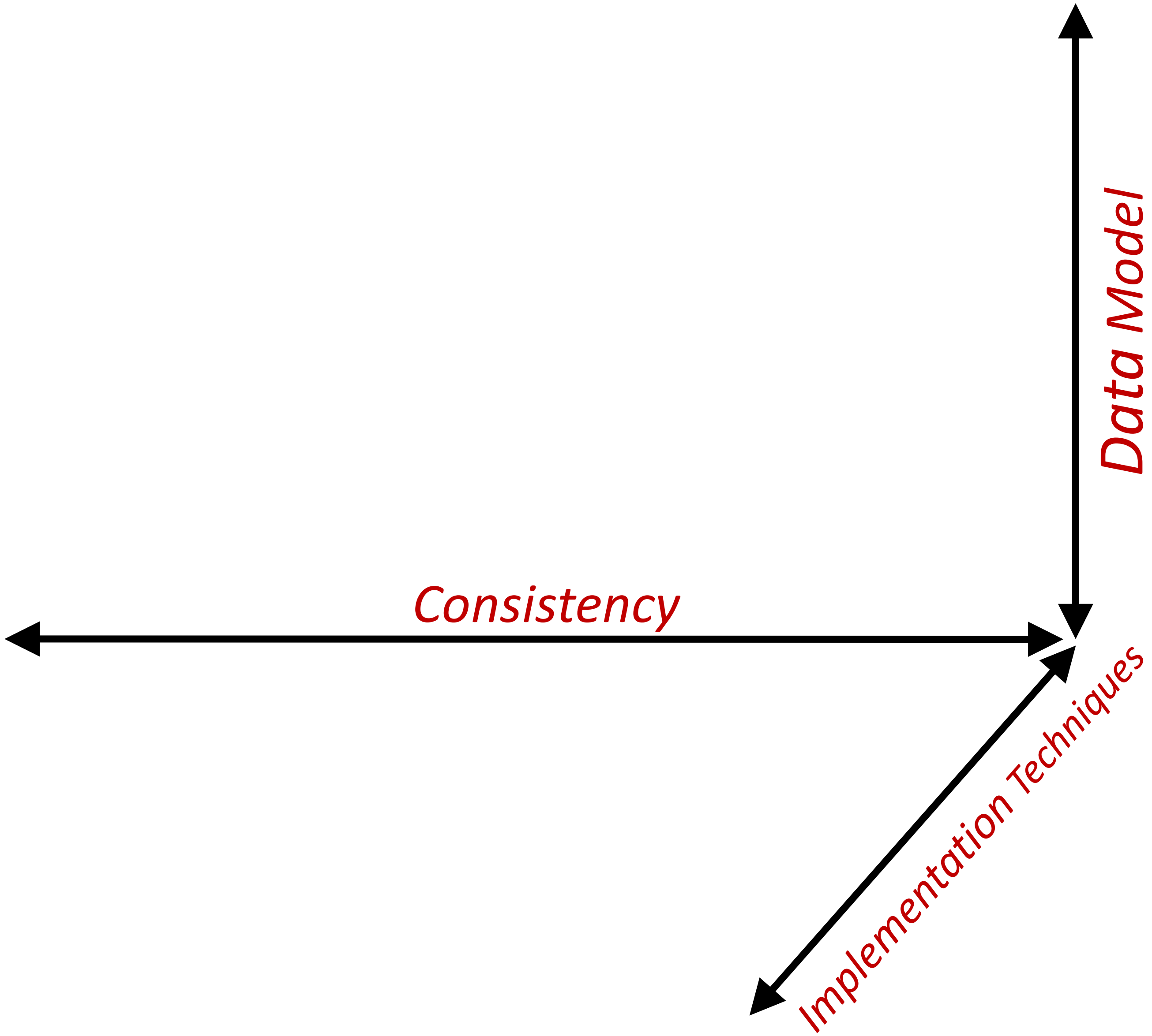

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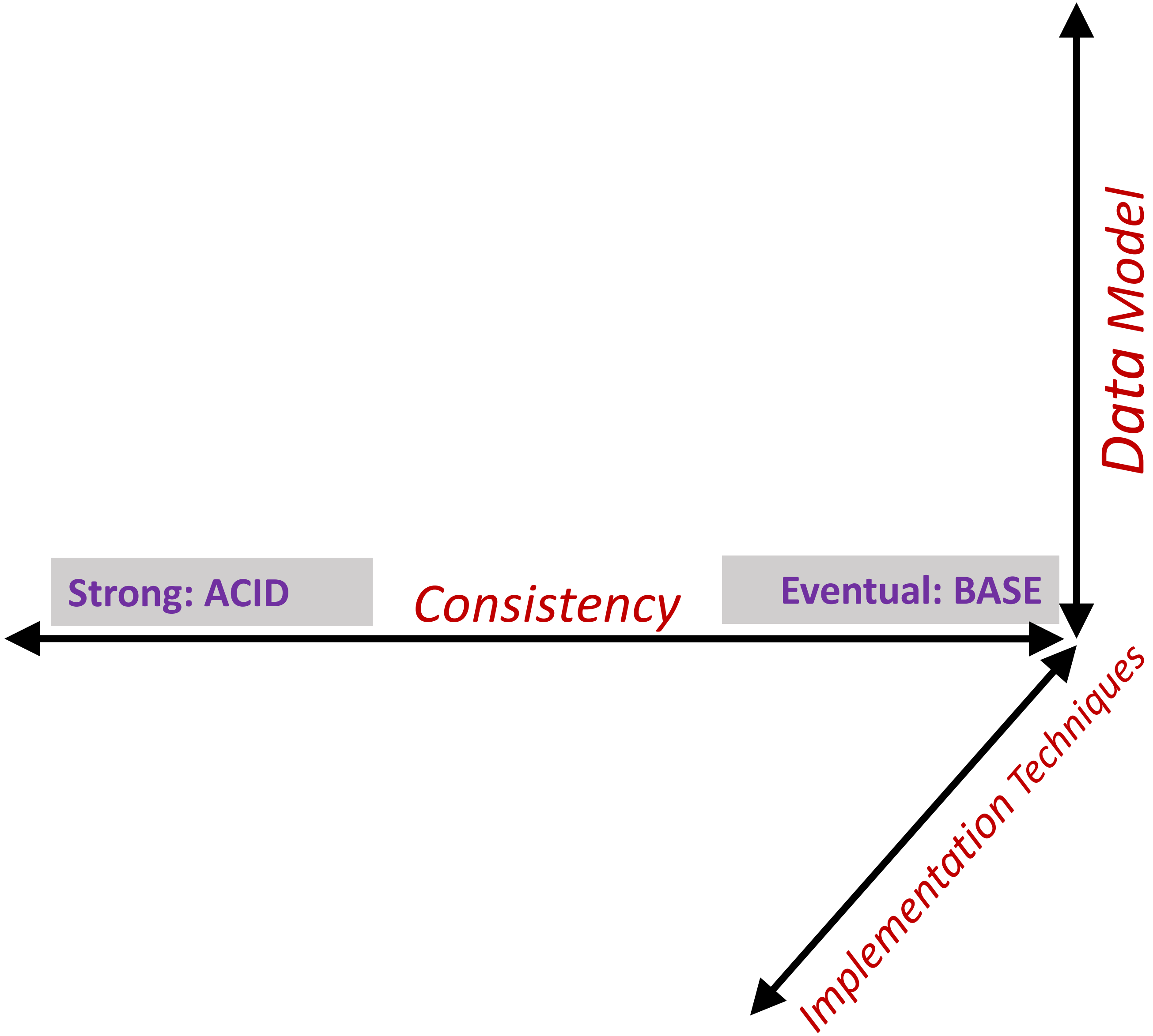


Strong: ACID

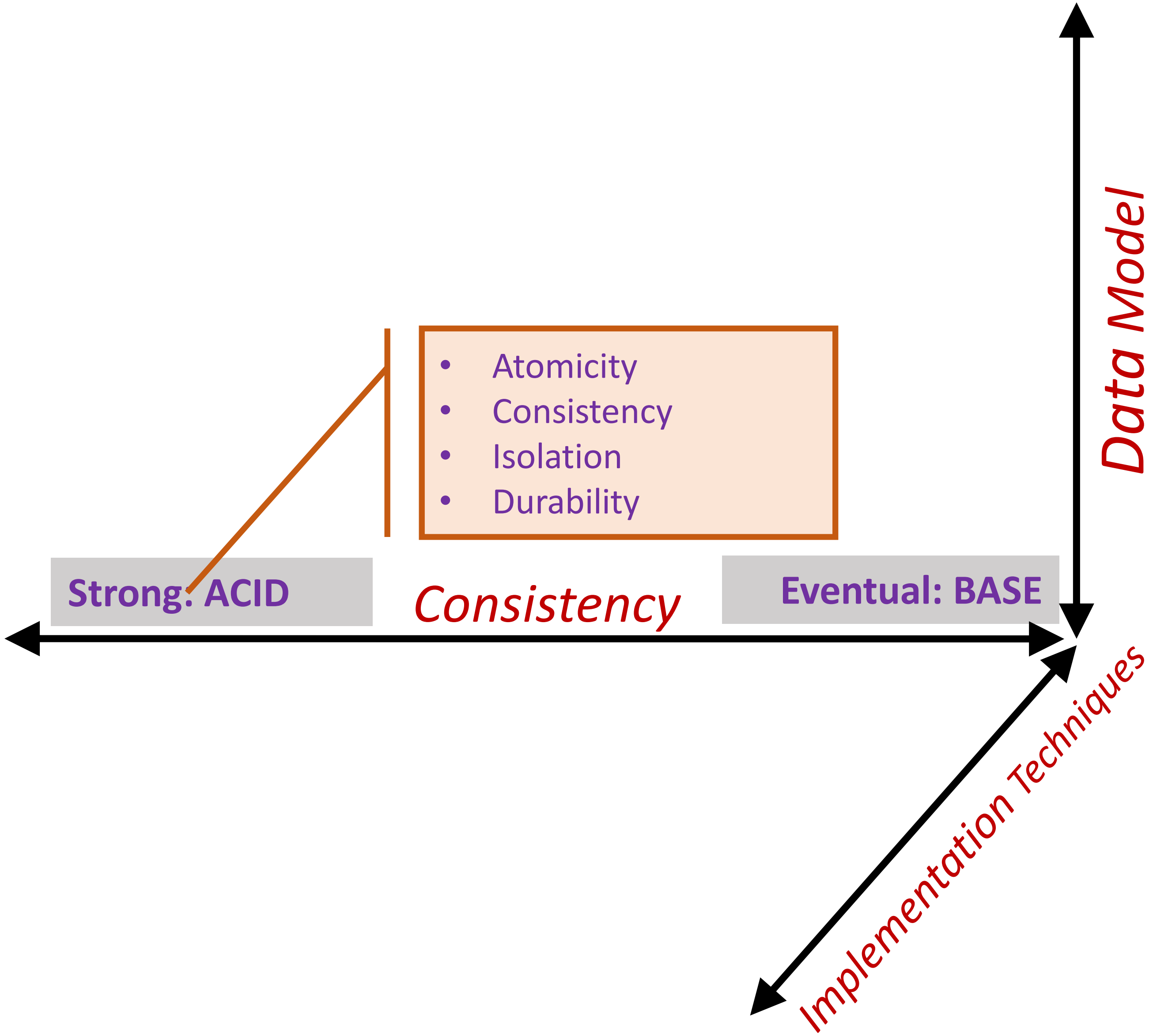
Consistency

Eventual: BASE

Data Model

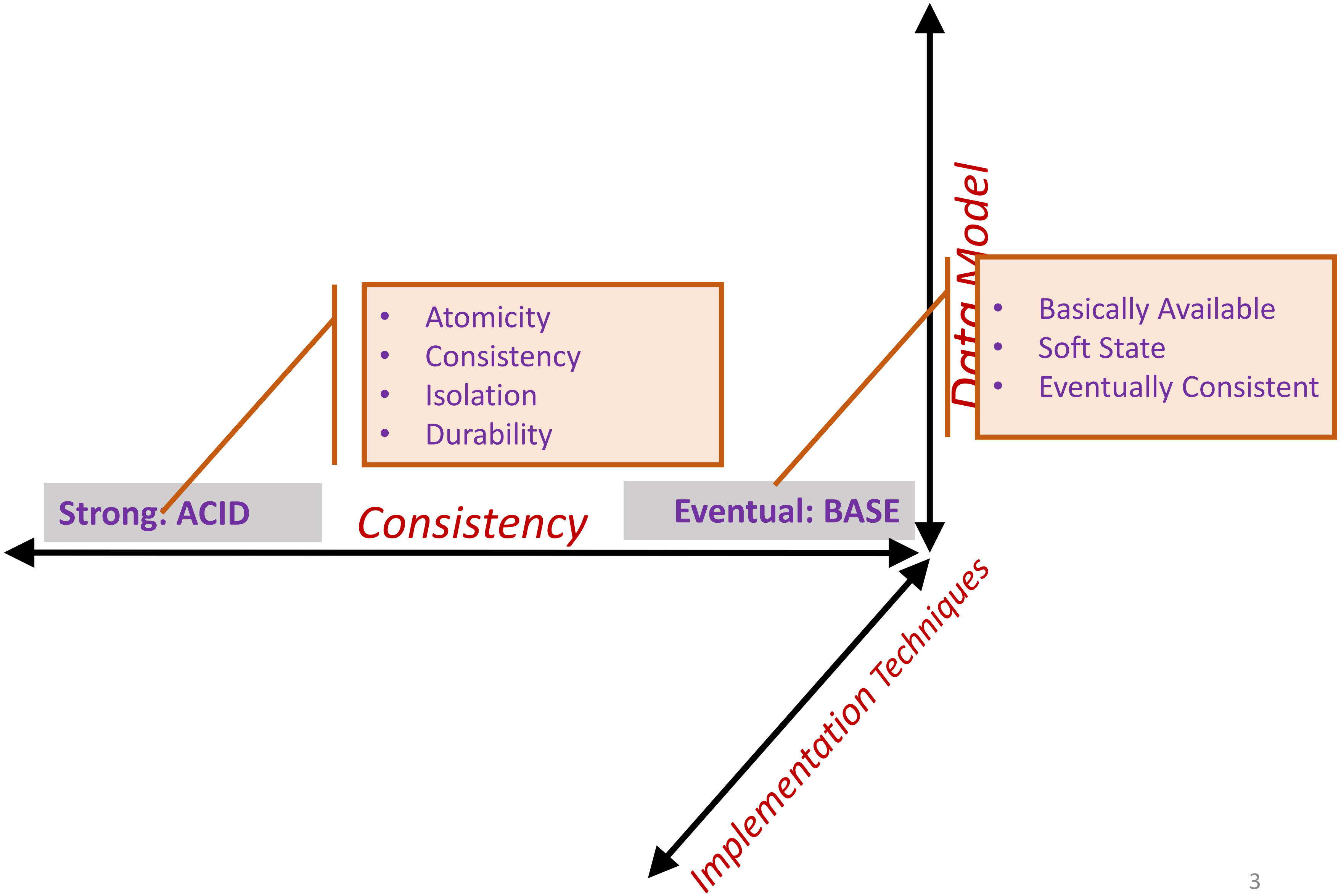
Implementation Techniques

Review: Another Framework



- Atomicity
- Consistency
- Isolation
- Durability

Review: Another Framework



Strong: ACID

- Atomicity
- Consistency
- Isolation
- Durability

Consistency

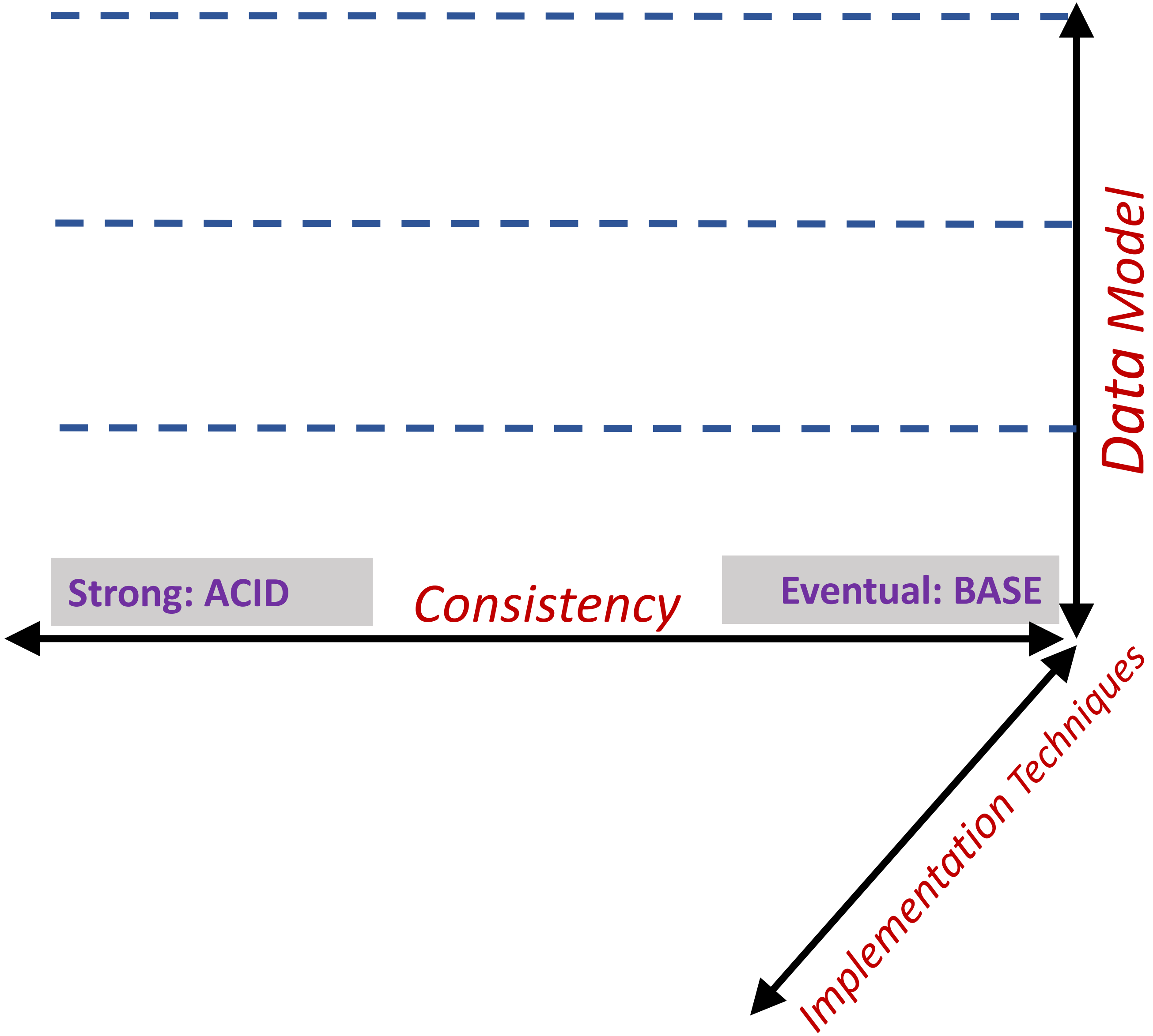
Eventual: BASE

- Basically Available
- Soft State
- Eventually Consistent

Data Model

Implementation Techniques

Review: Another Framework



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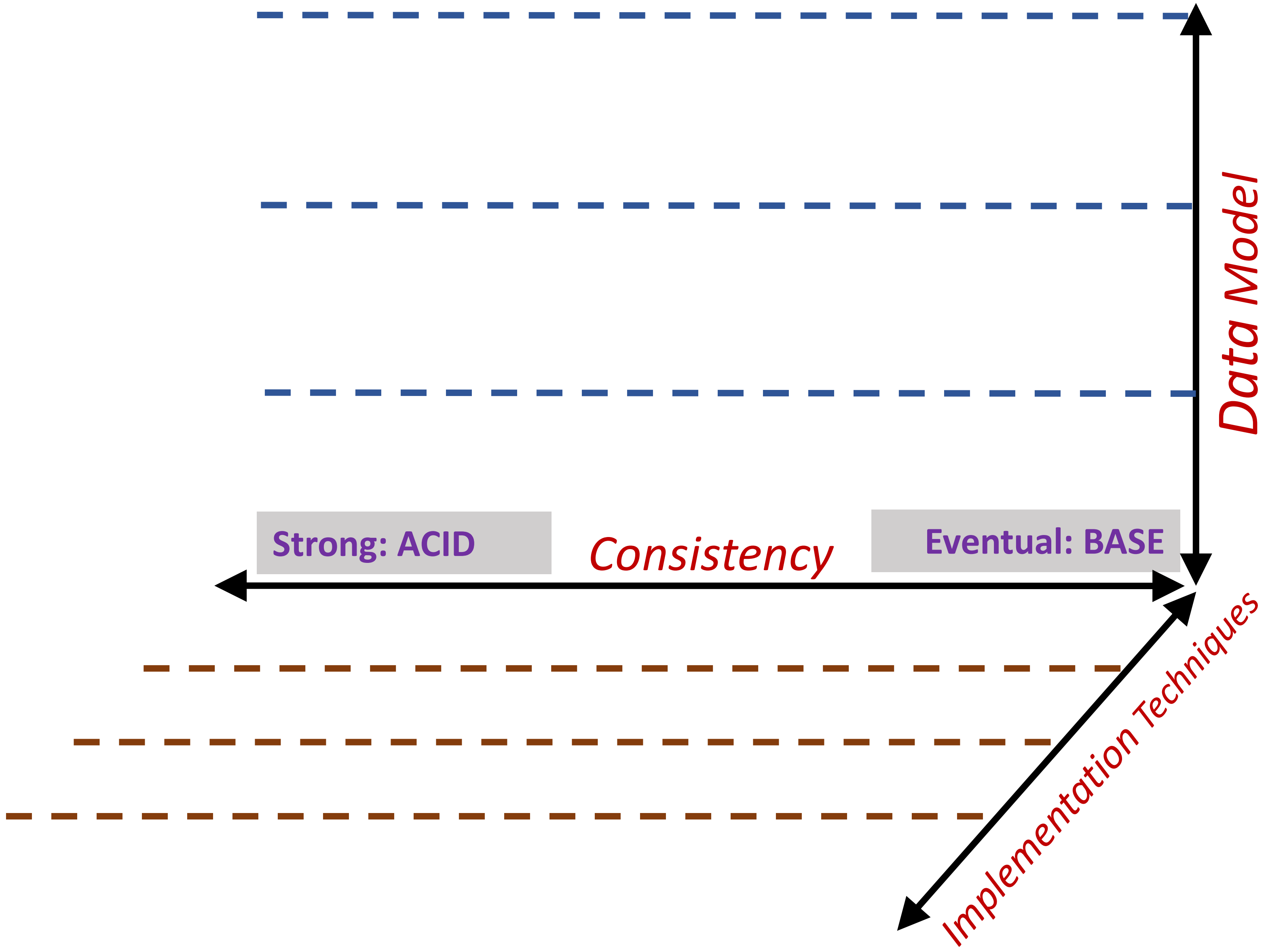

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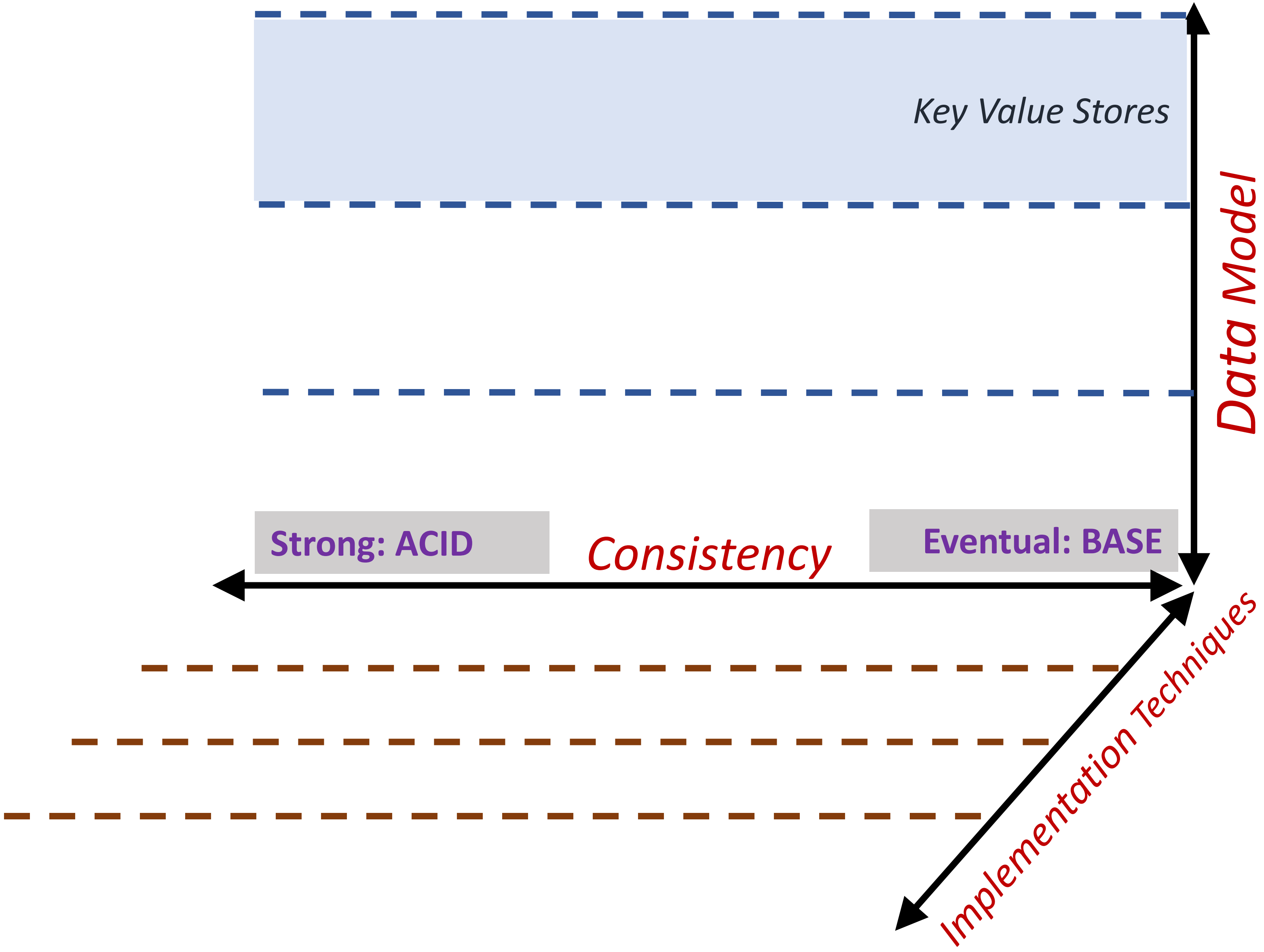

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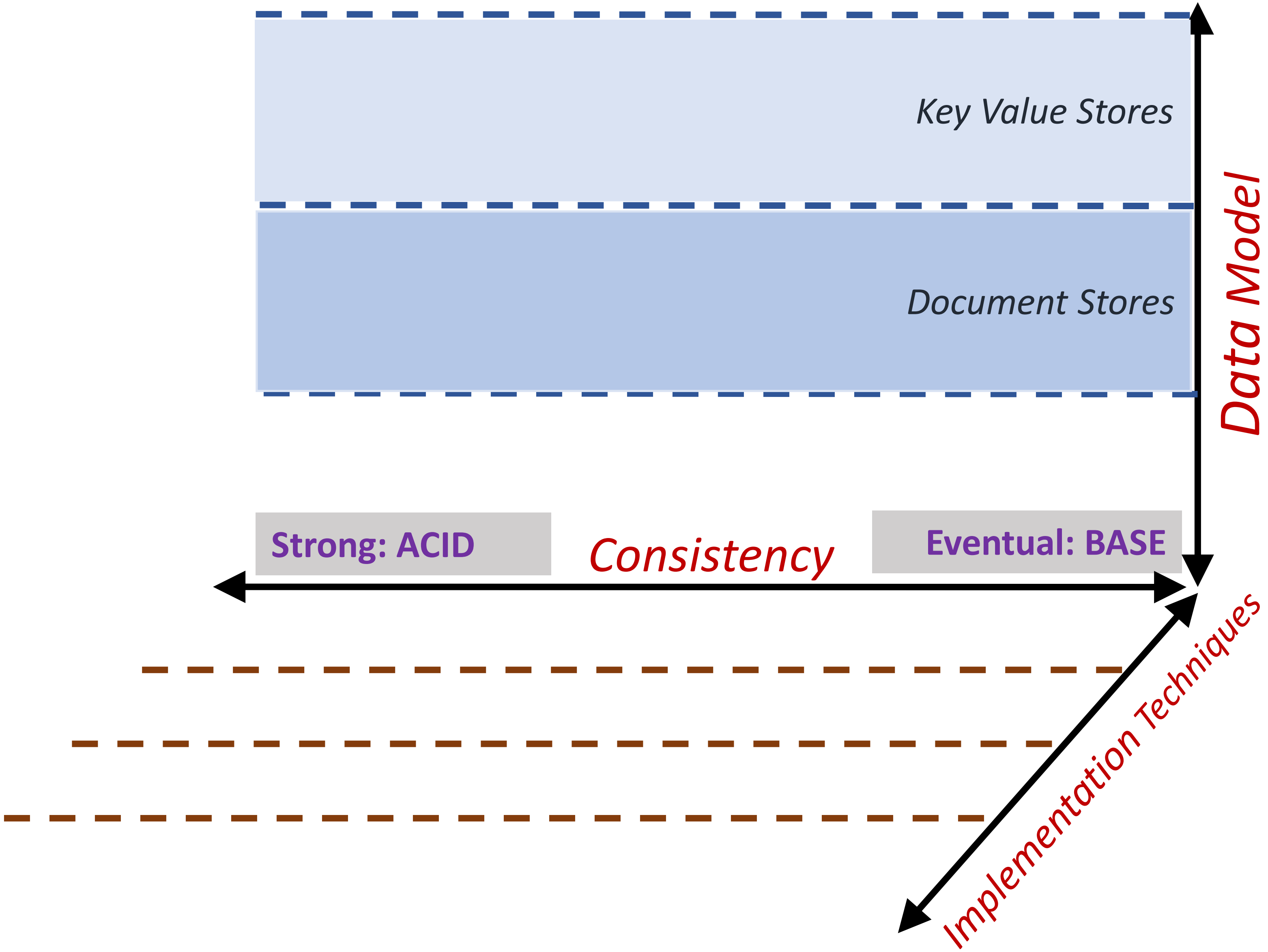

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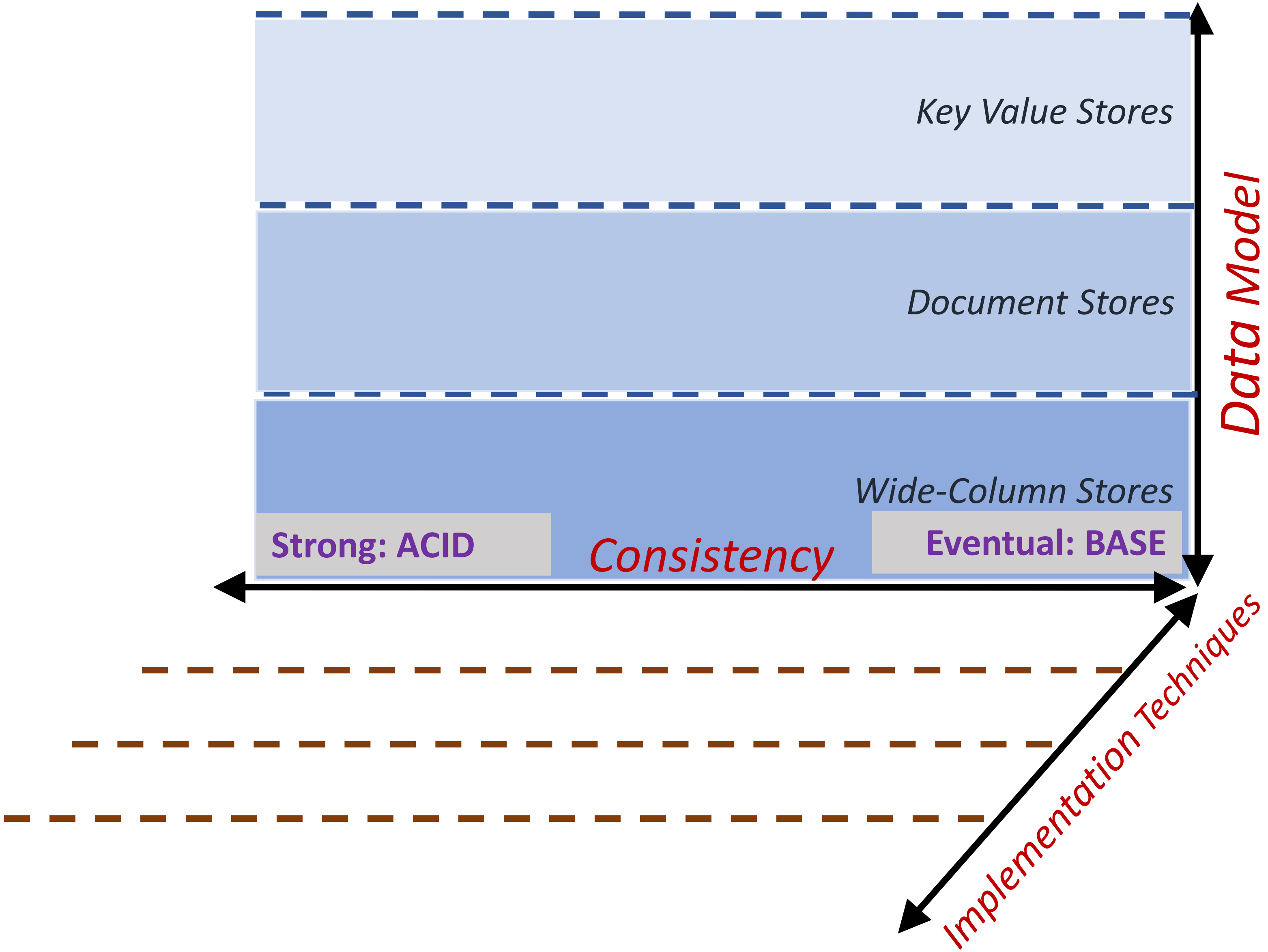

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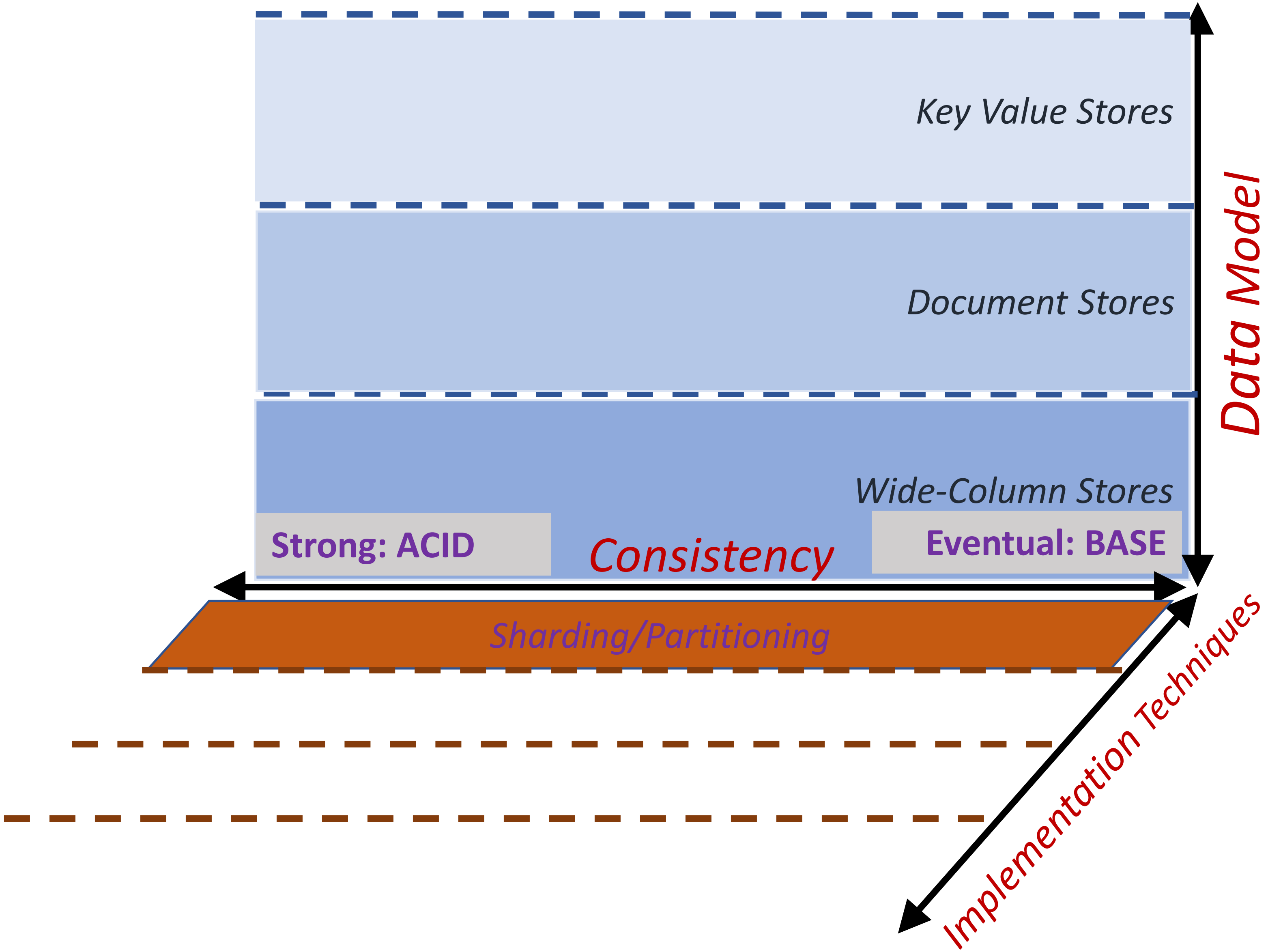

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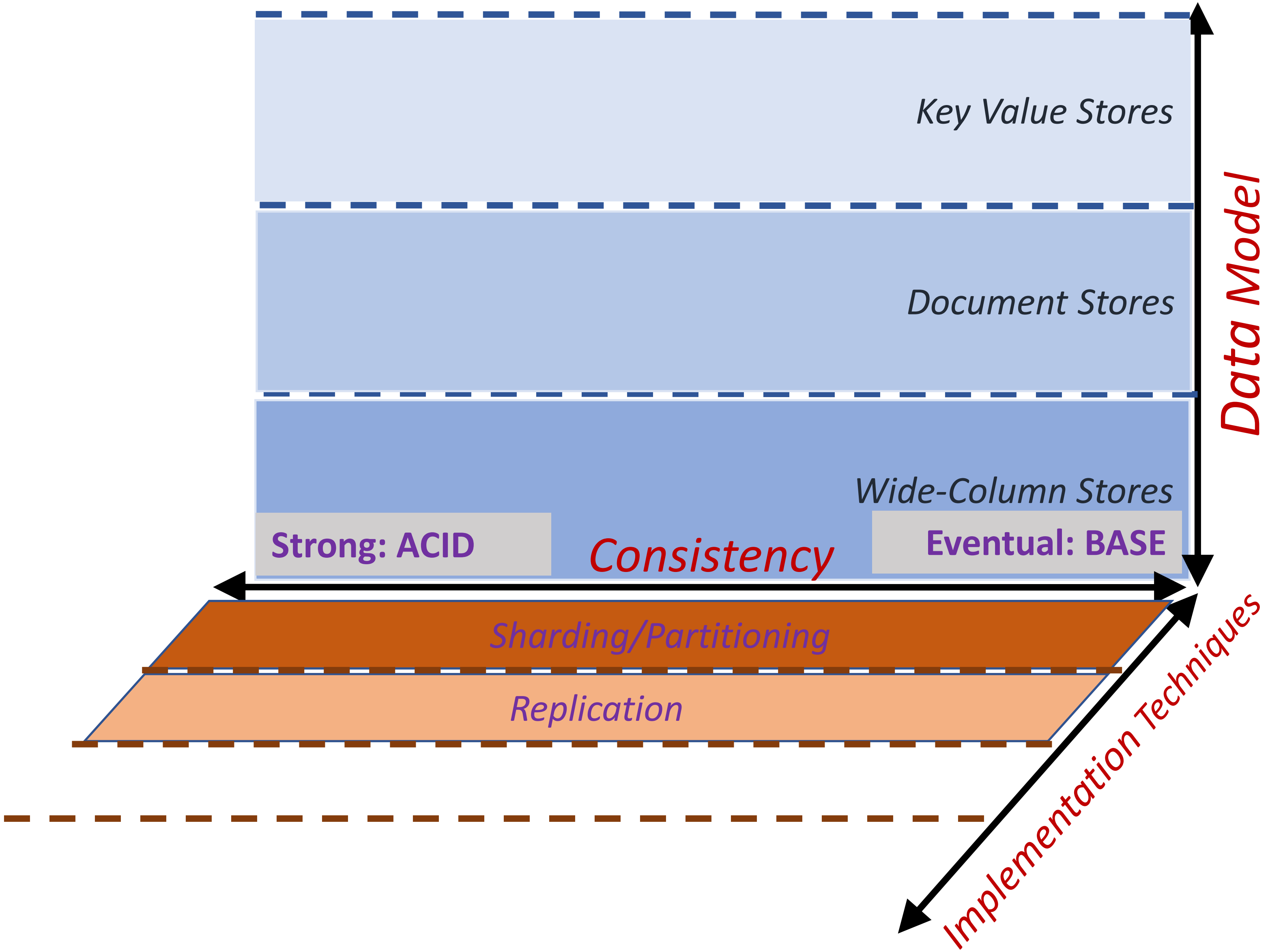

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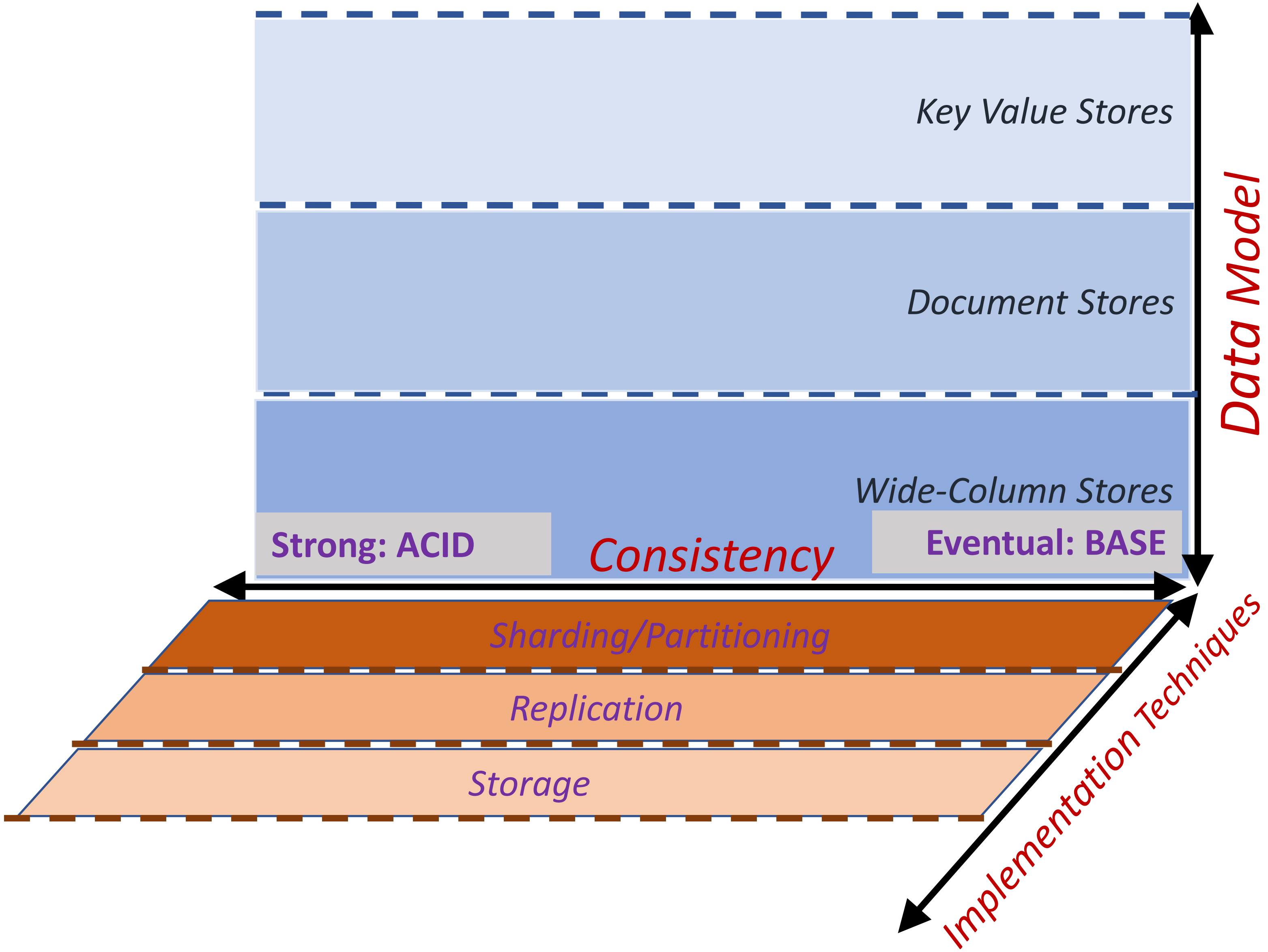

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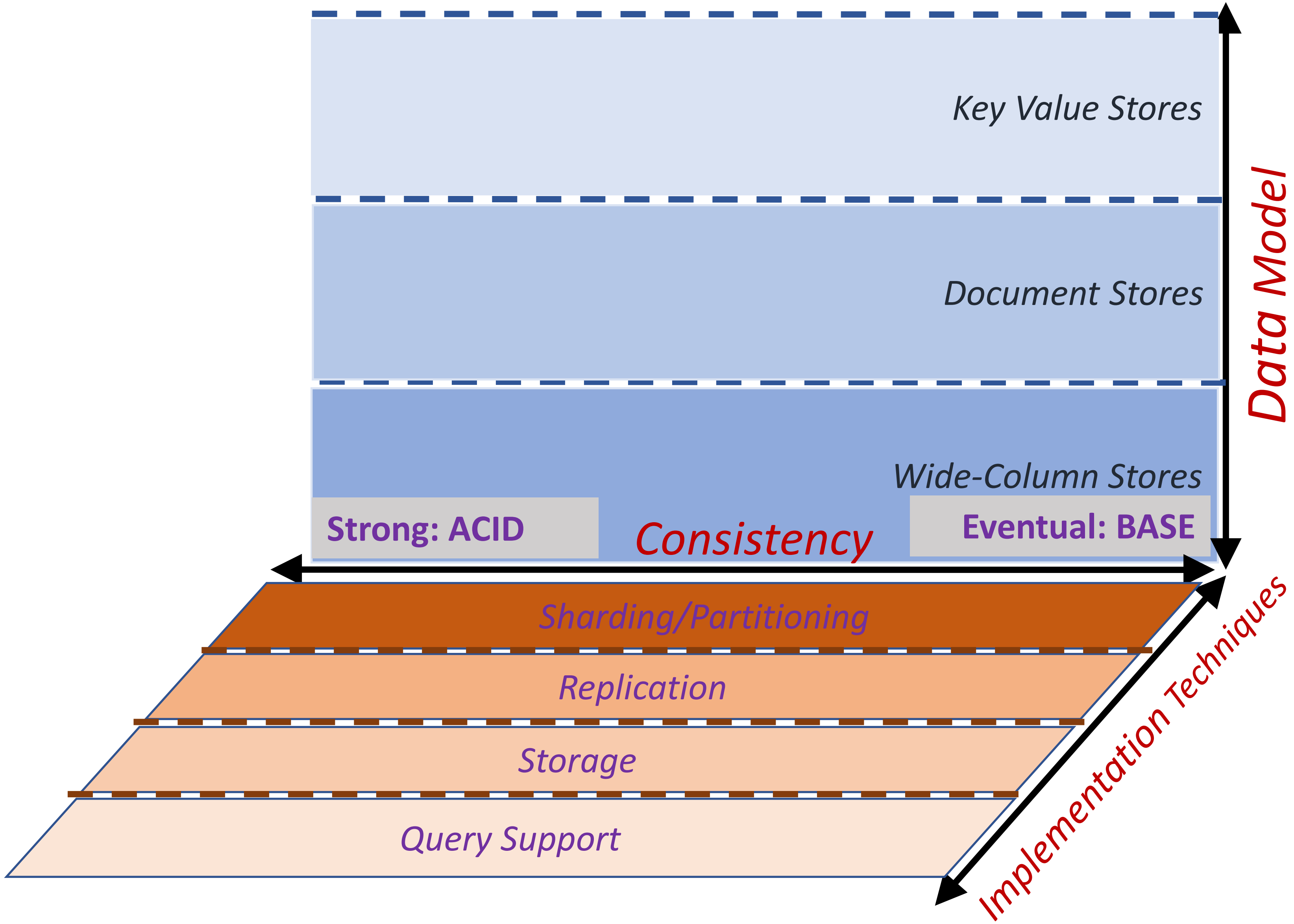

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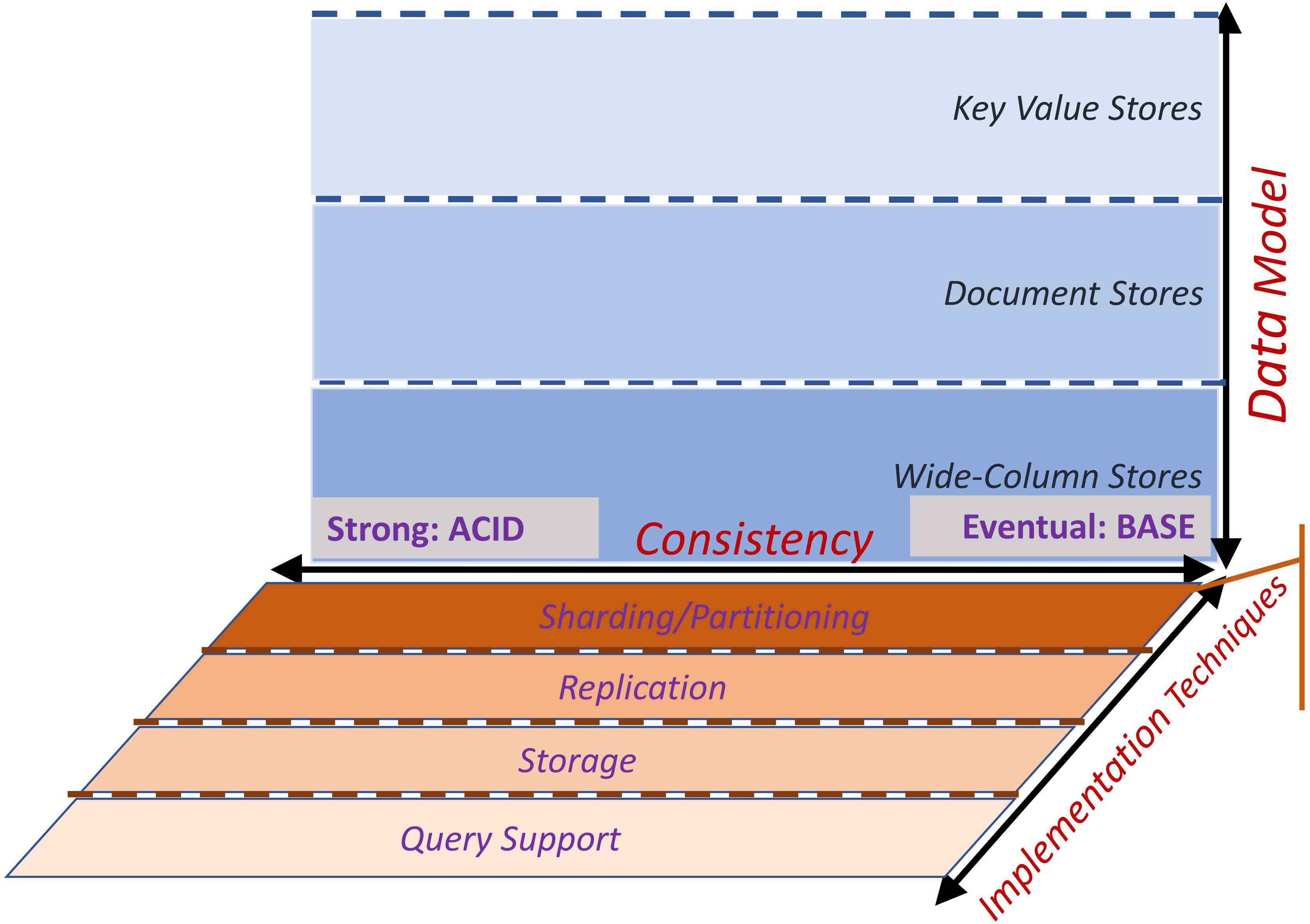
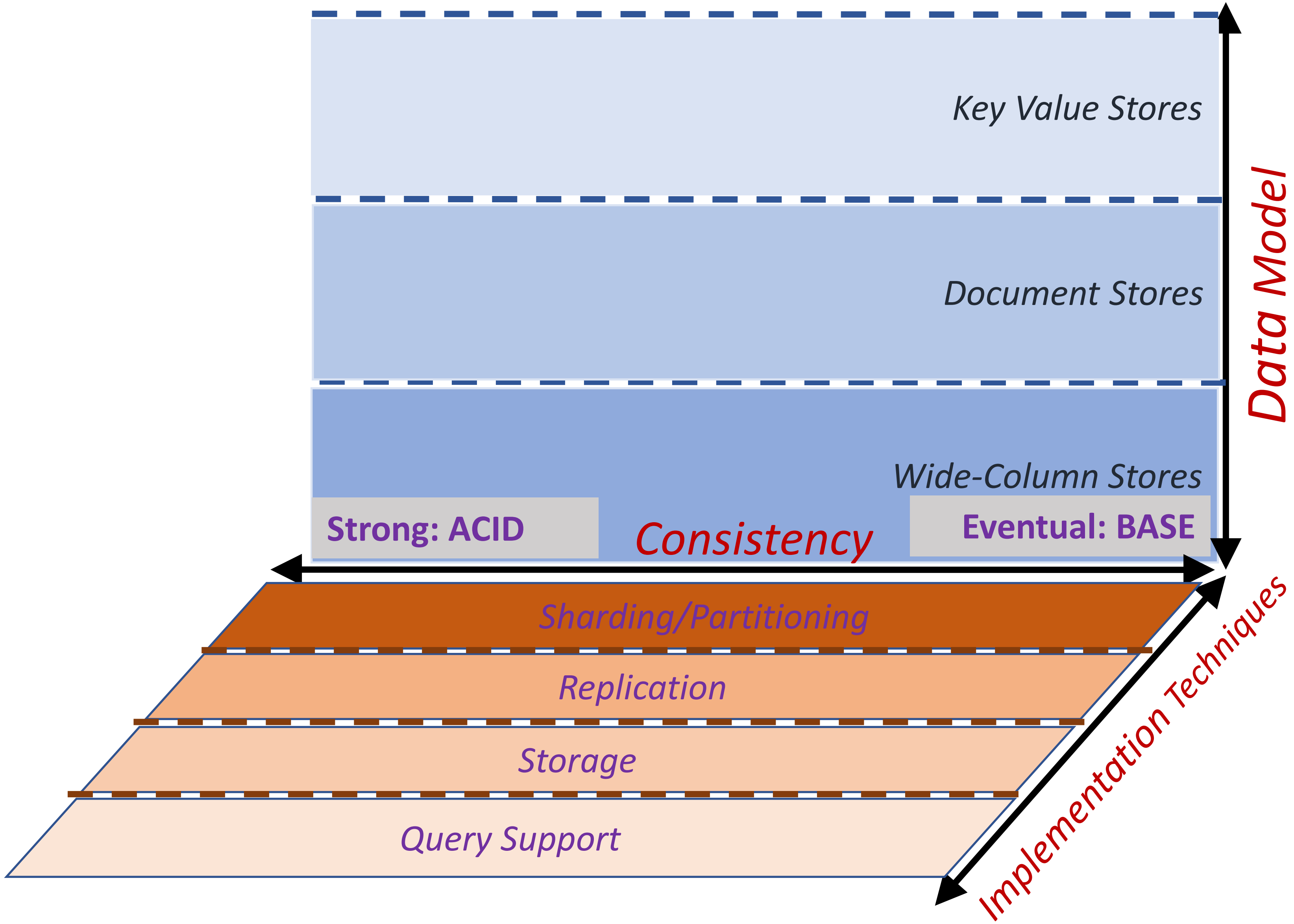


- Shared-Disk
- Range-Sharding
- Hash-Sharding
- Consistent Hashing

Review: Another Framework



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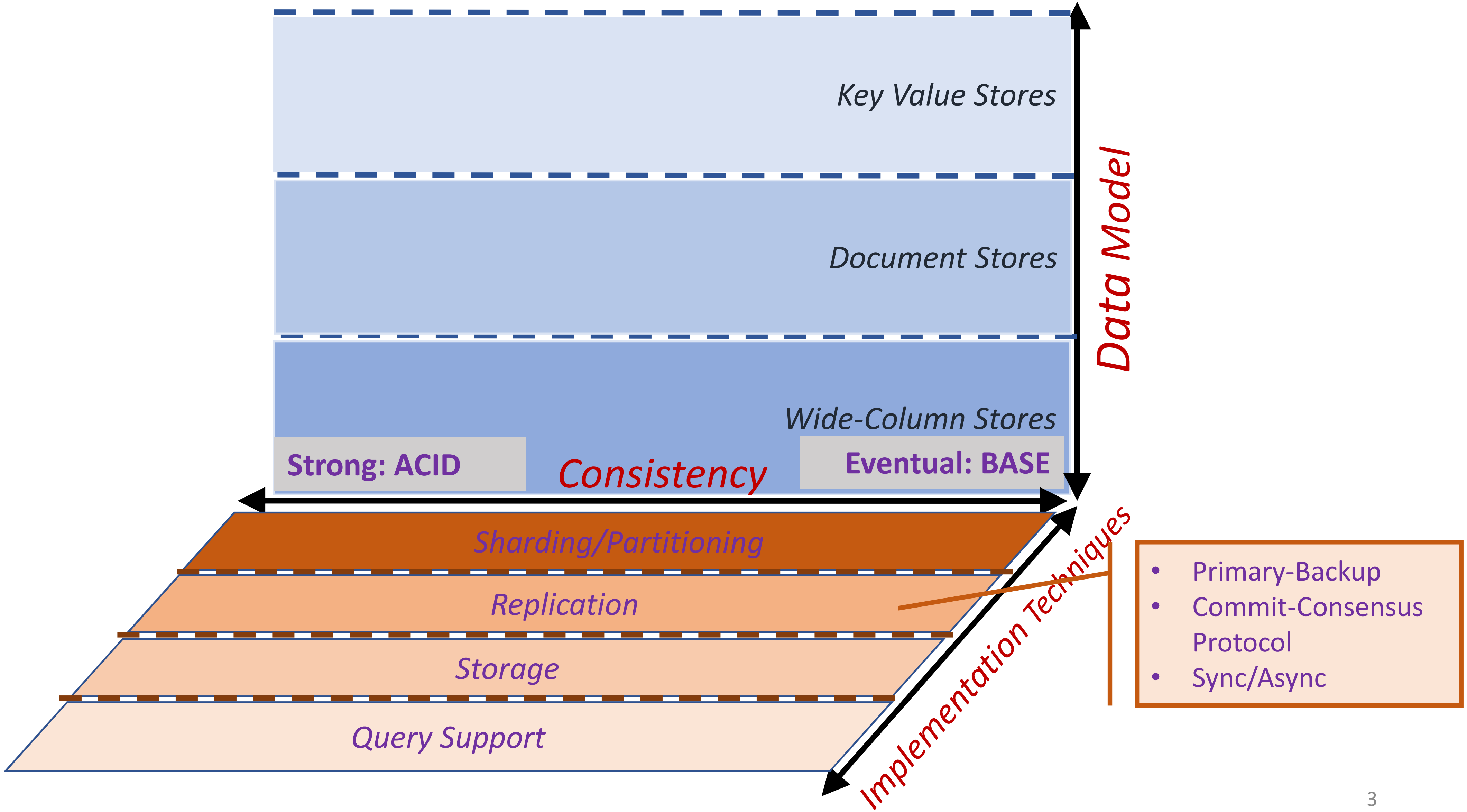

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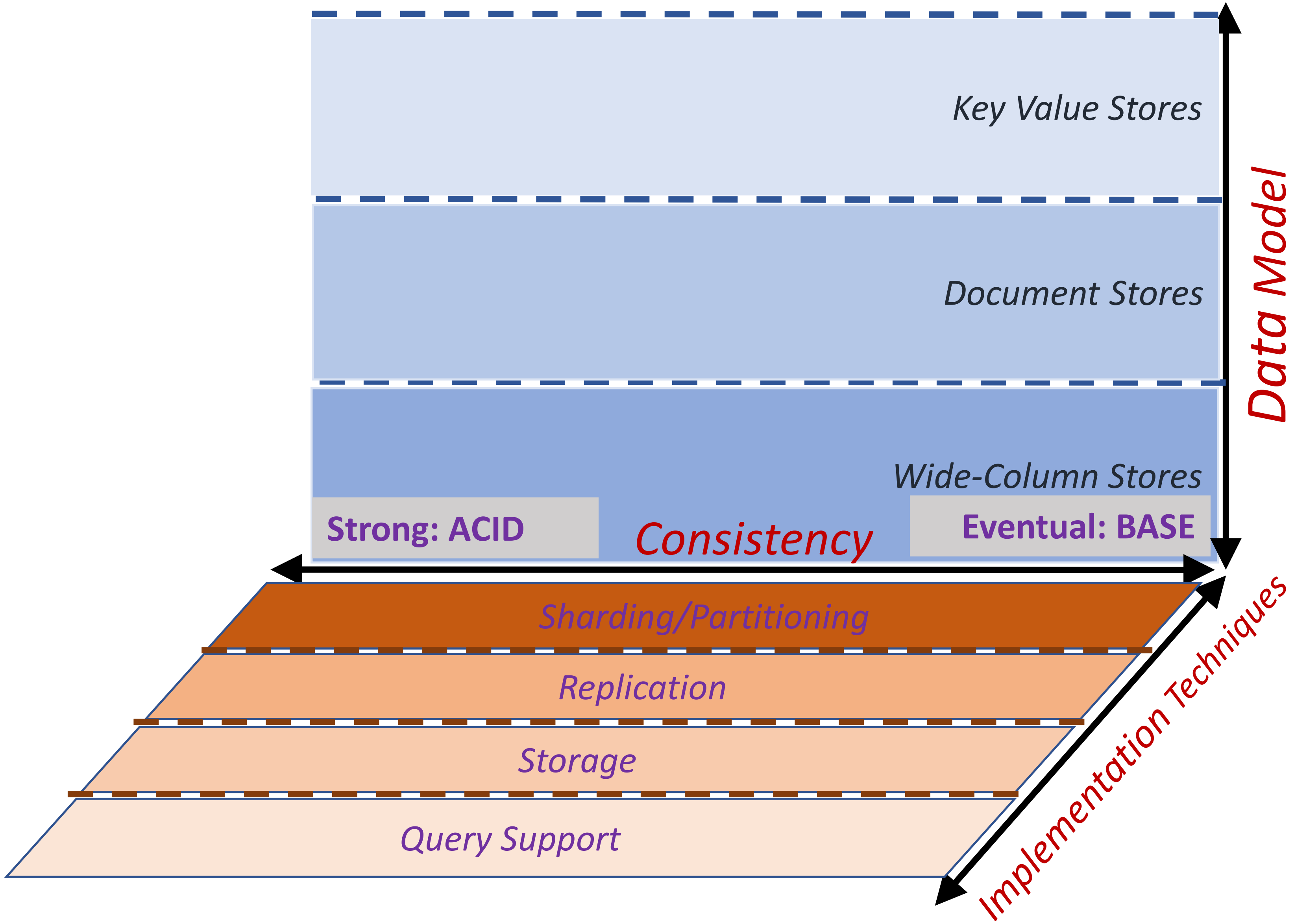

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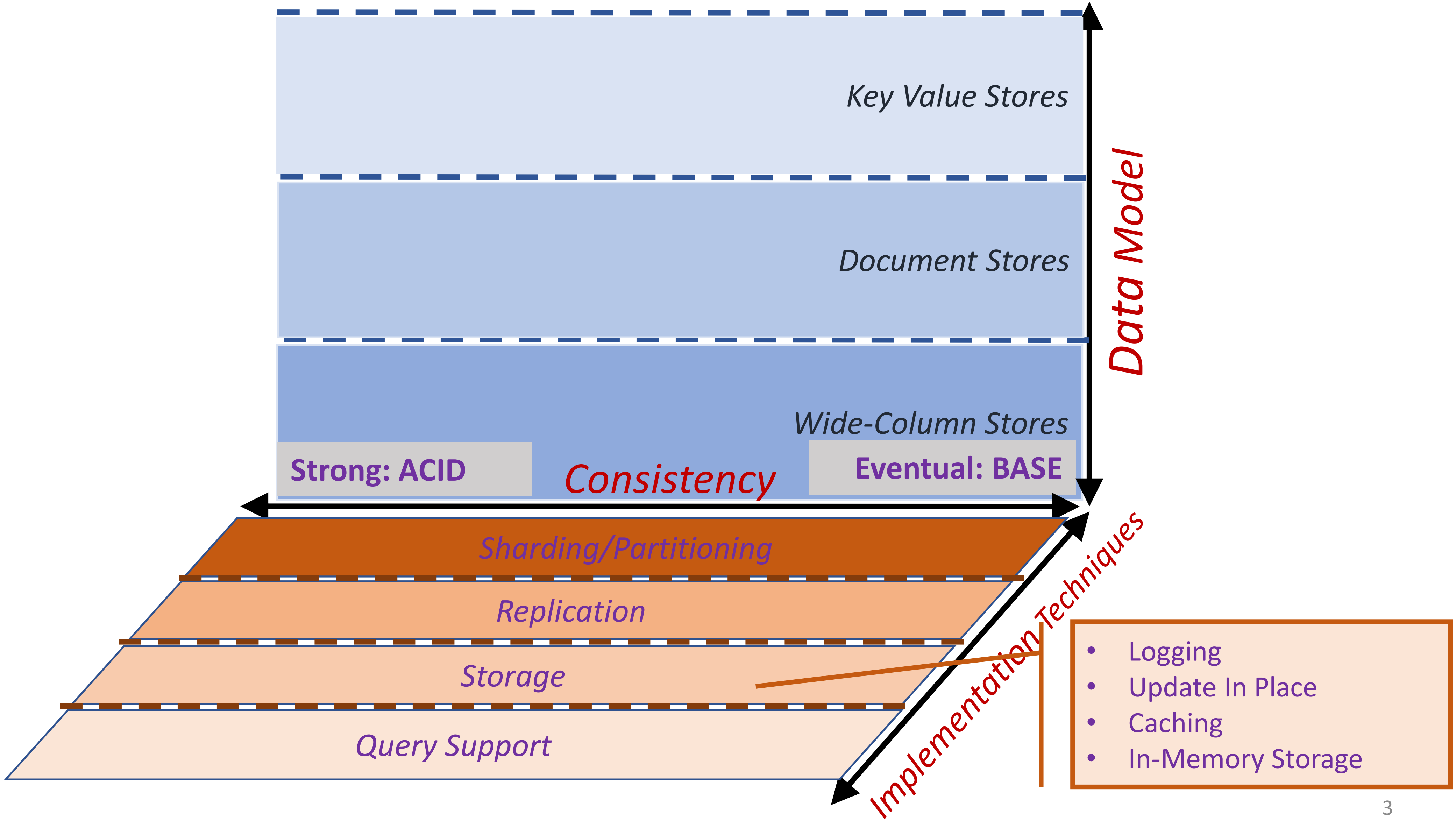
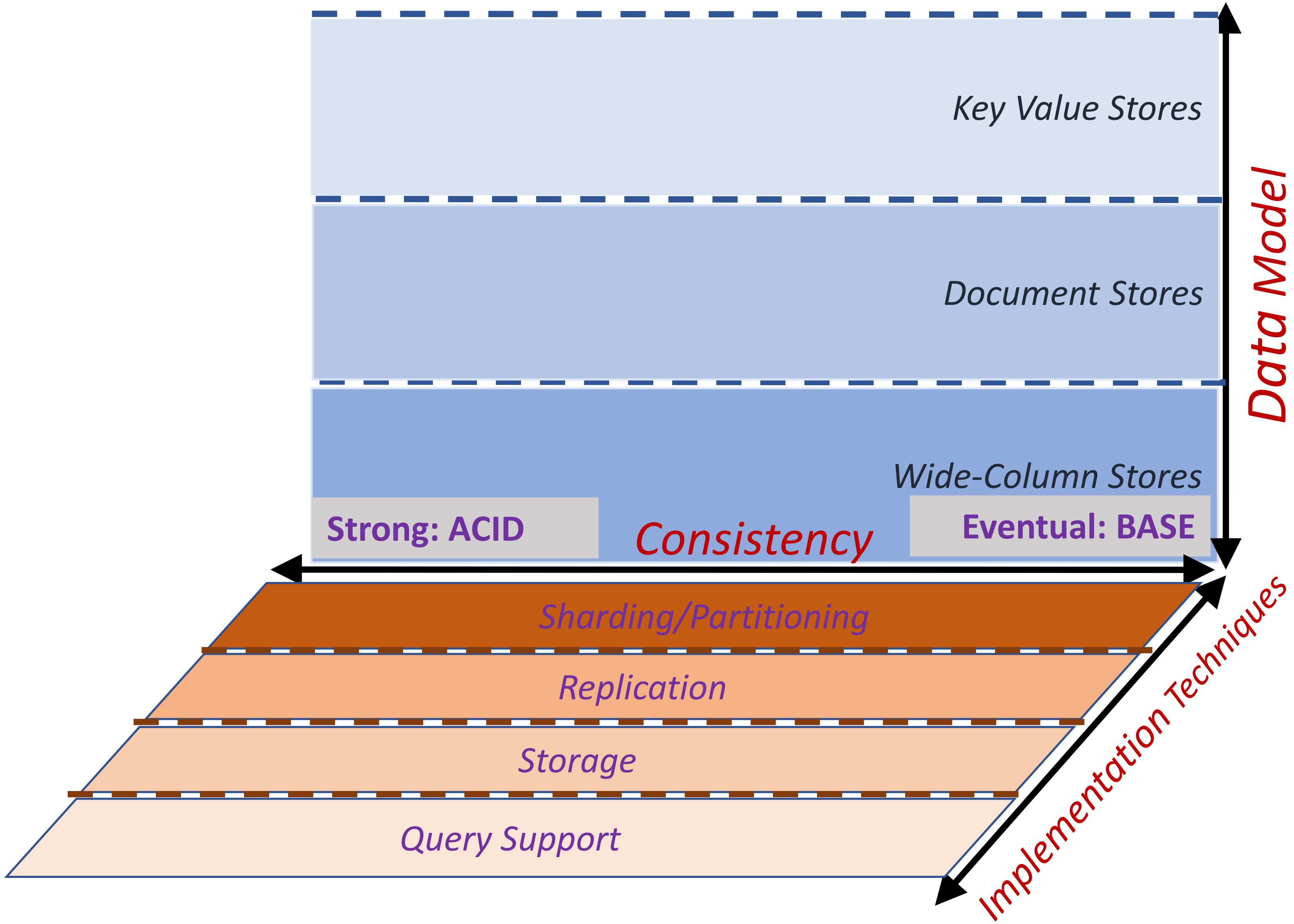


- Logging
- Update In Place
- Caching
- In-Memory Storage

Review: Another Framework



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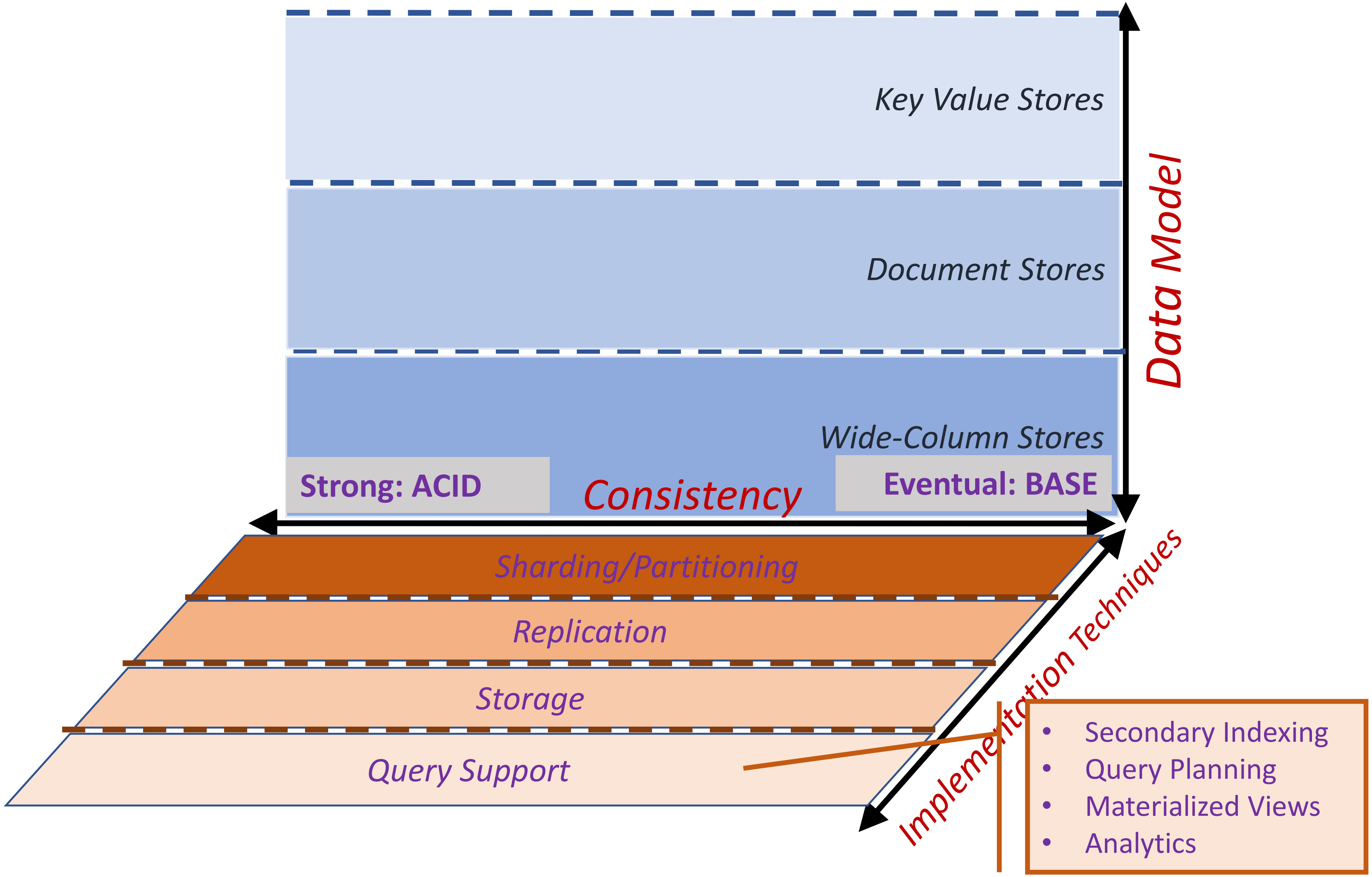

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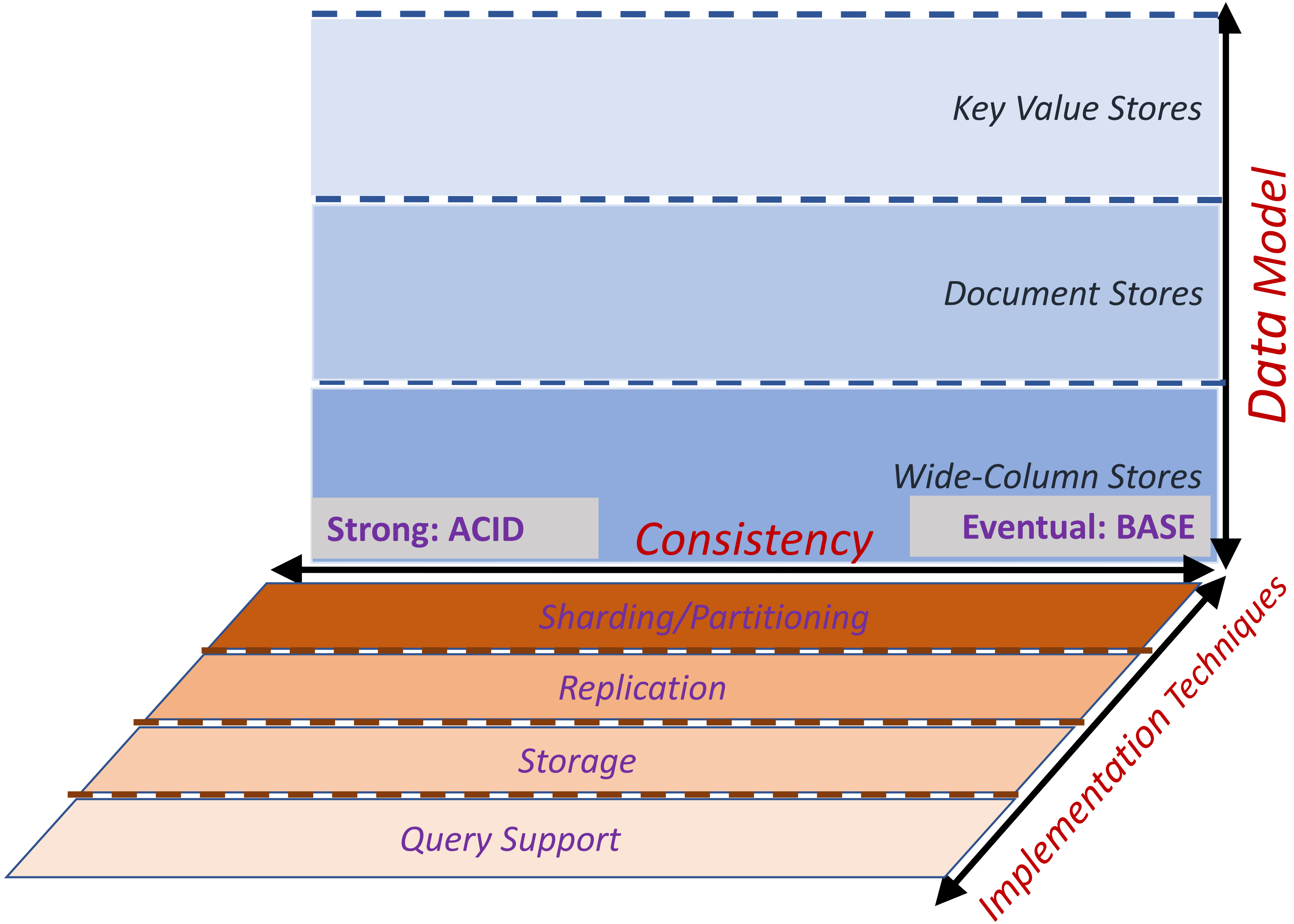


Review: Another Framework

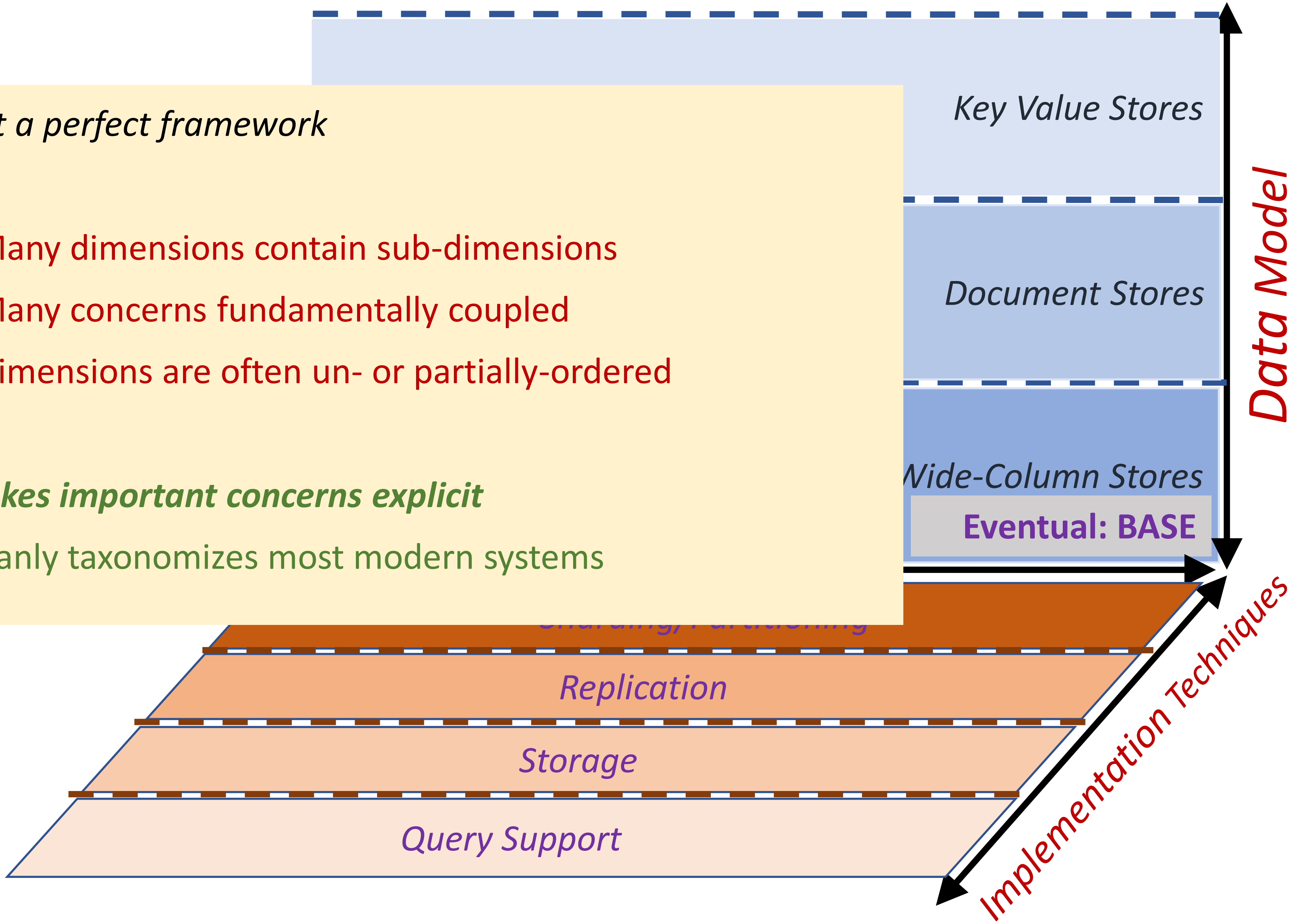
Still not a perfect framework

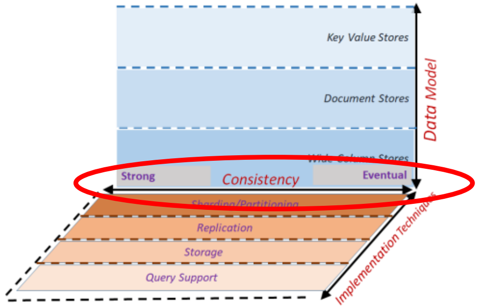
Cons:

- Many dimensions contain sub-dimensions
- Many concerns fundamentally coupled
- Dimensions are often un- or partially-ordered

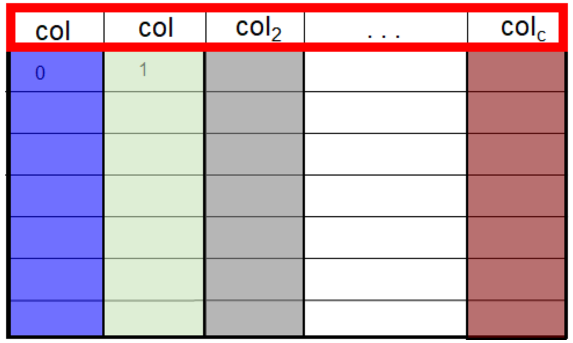
Pros:

- ***Makes important concerns explicit***
- Cleanly taxonomizes most modern systems





Consistency



col	col	col_2	. . .	col_c
0	1			

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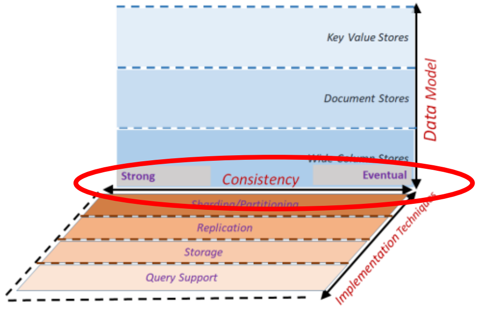

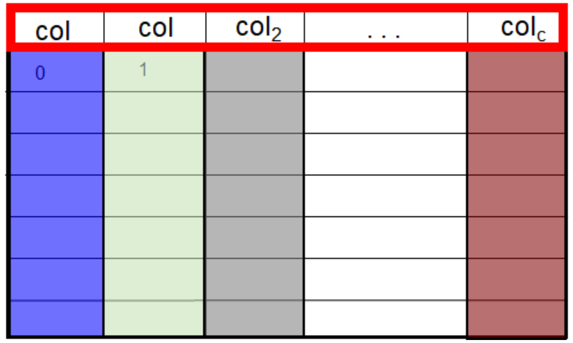

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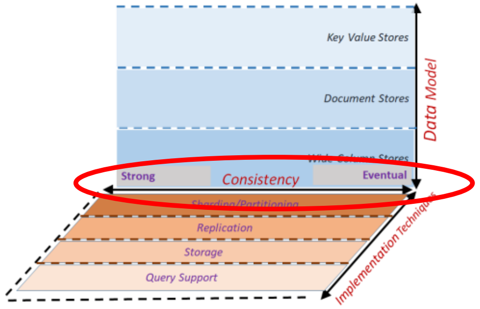
How to keep data in sync?



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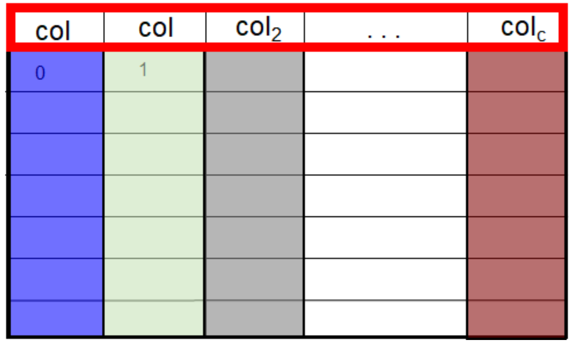
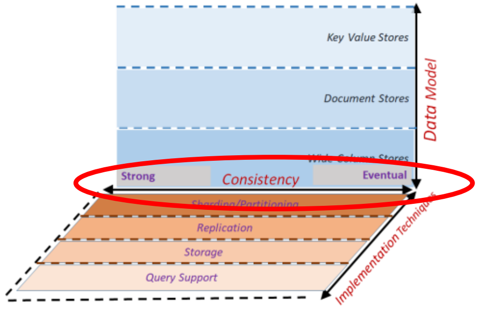


How to keep data in sync?

- Partitioning → single row spread over multiple machines



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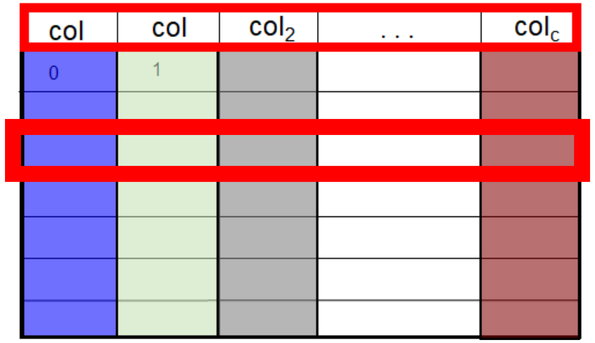

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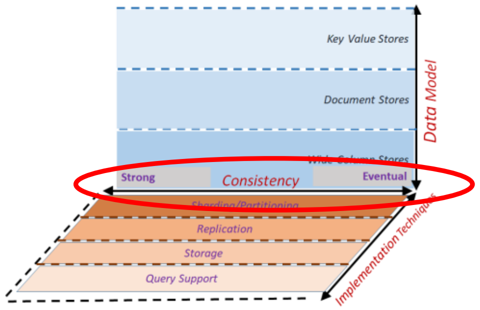

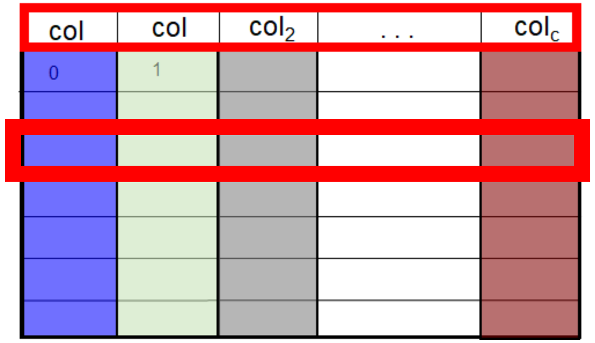

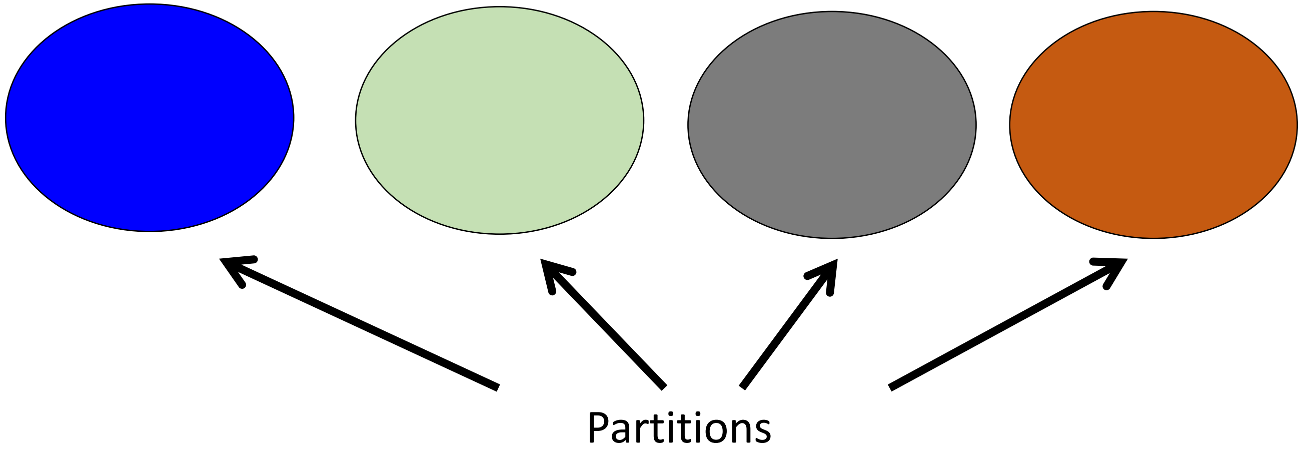

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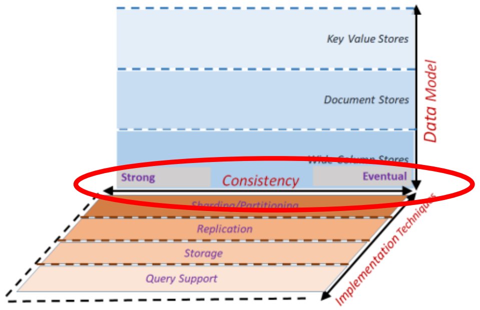
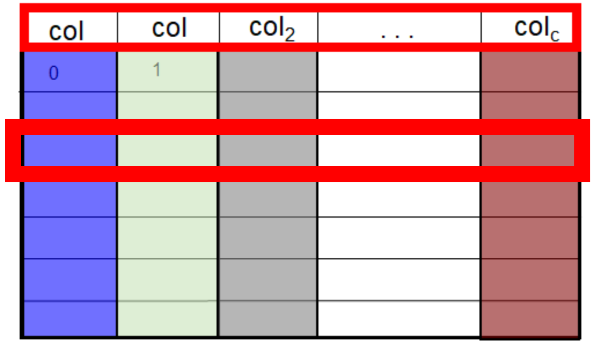
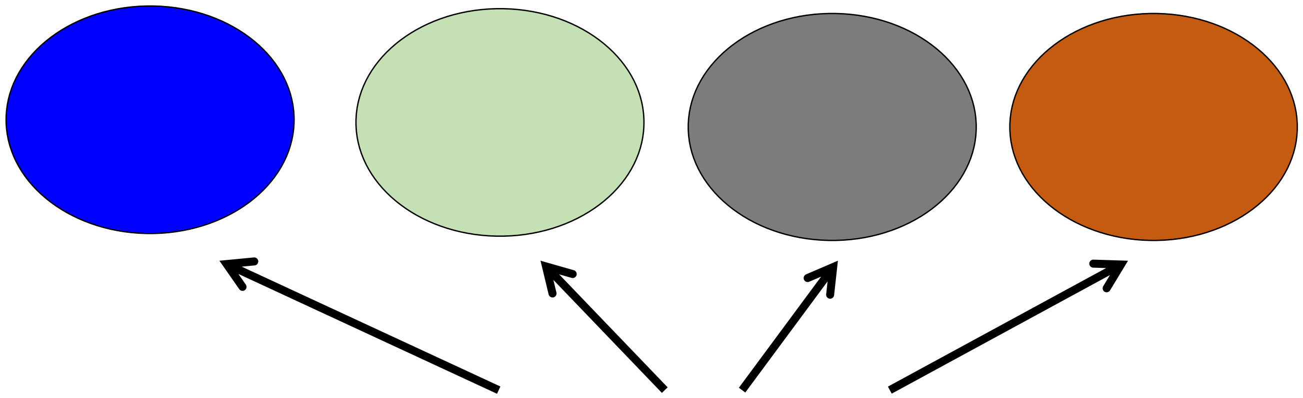




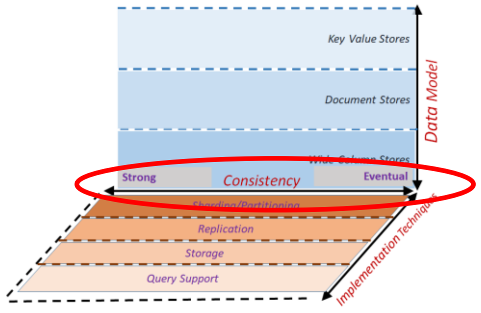


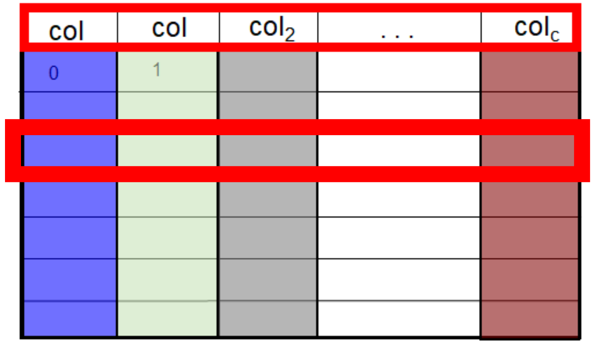
Partitions

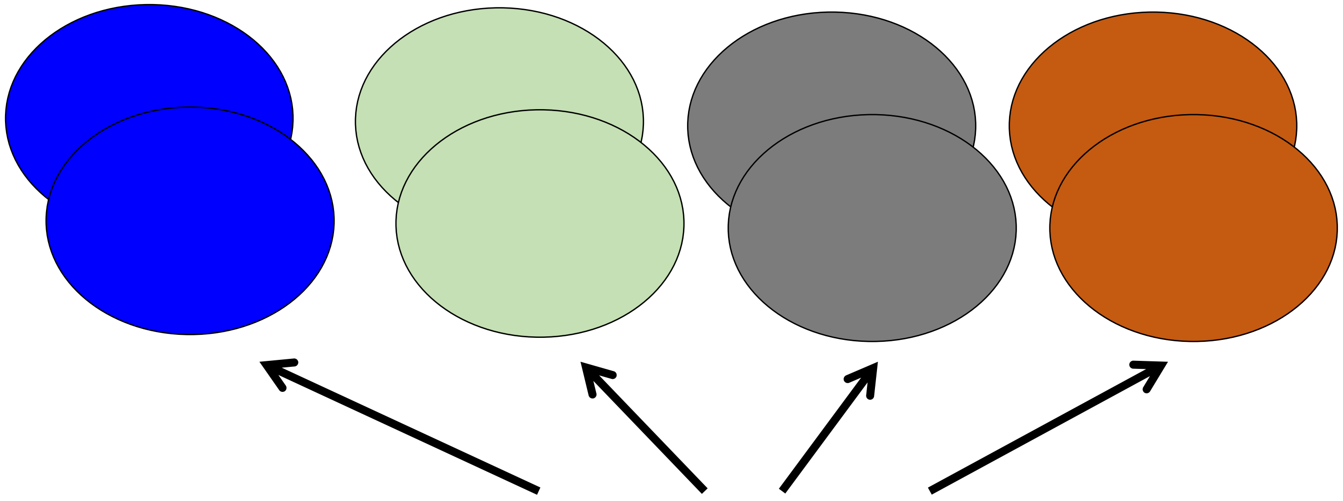
How to keep data in sync?

- Partitioning → single row spread over multiple machines
- Redundancy → single datum spread over multiple machines

Consistency







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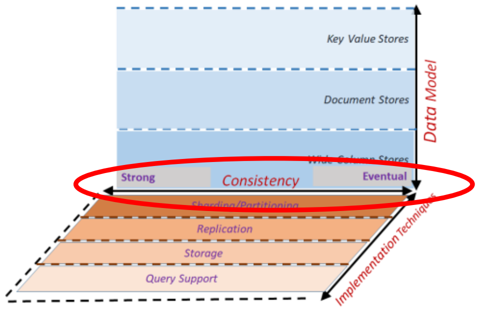

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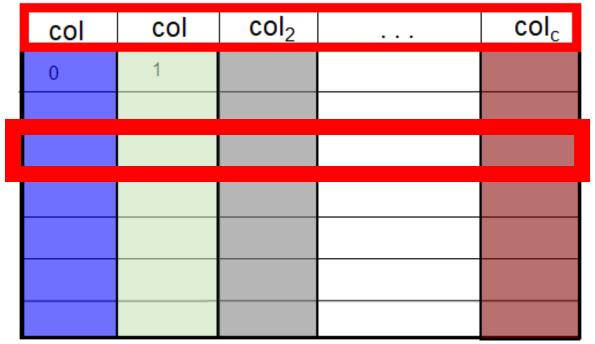

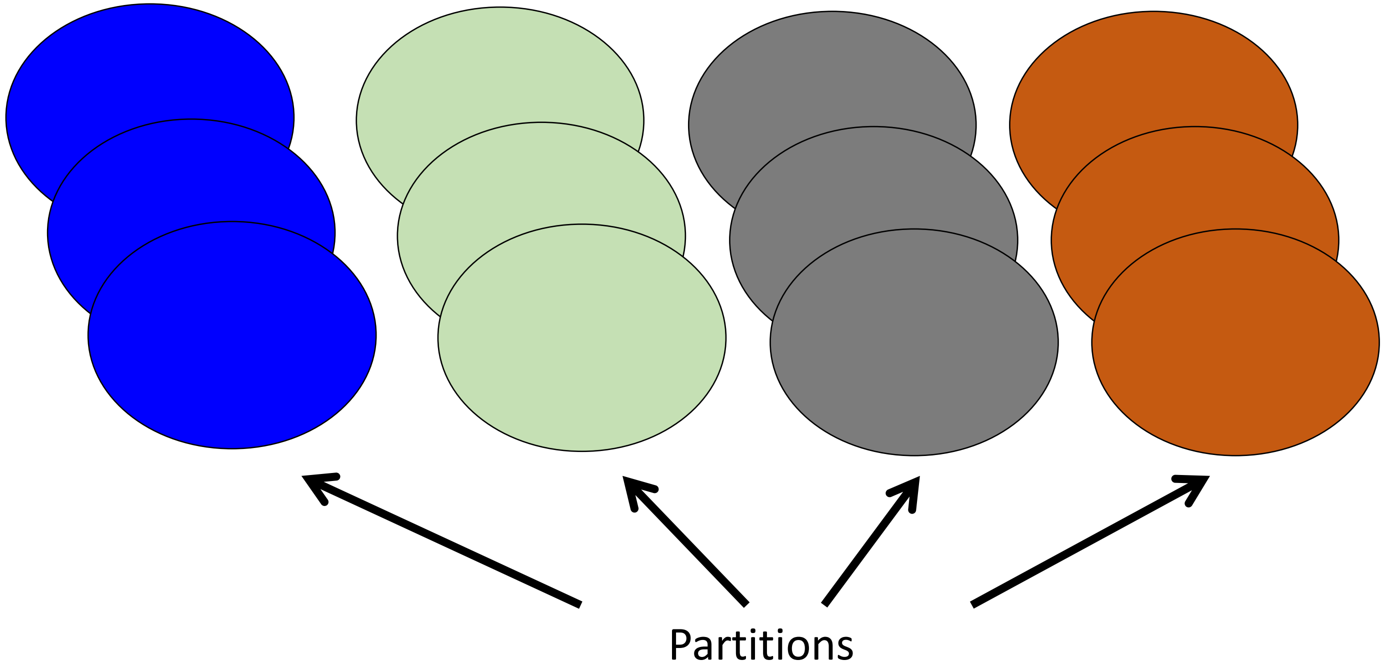

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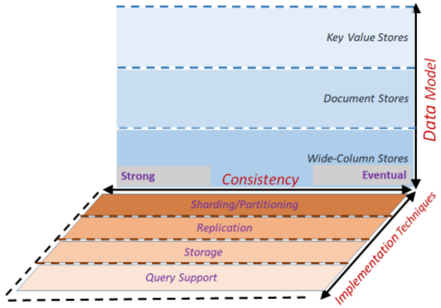
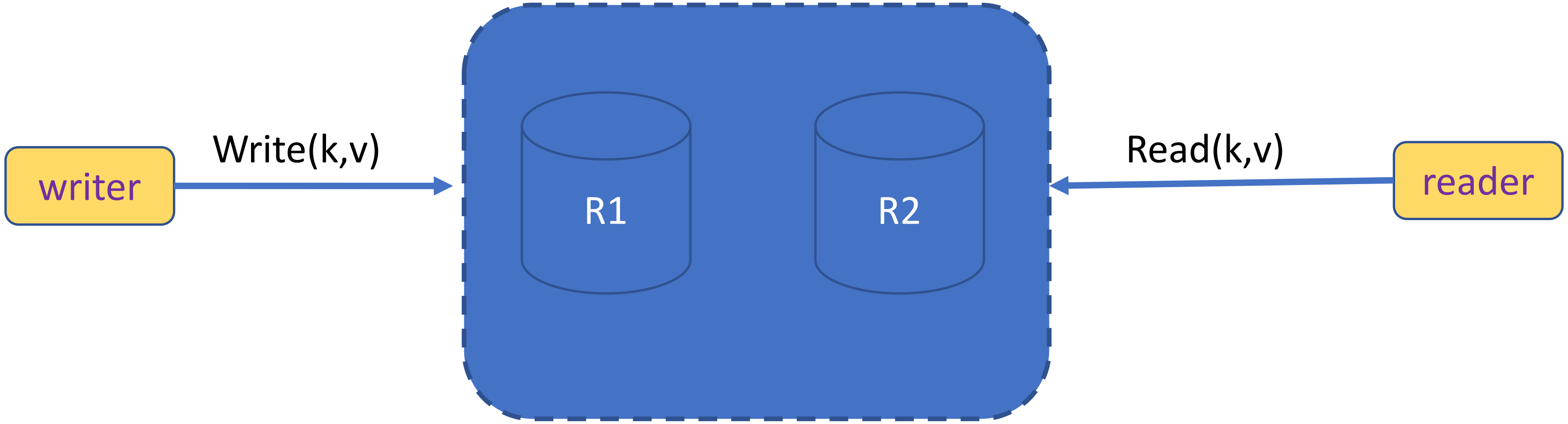
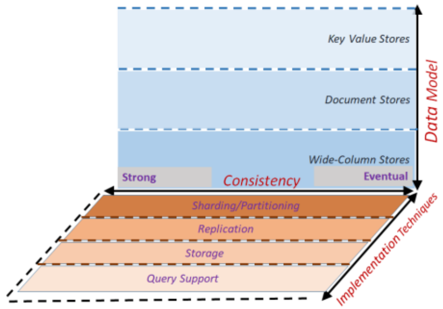


Consistency: the core problem





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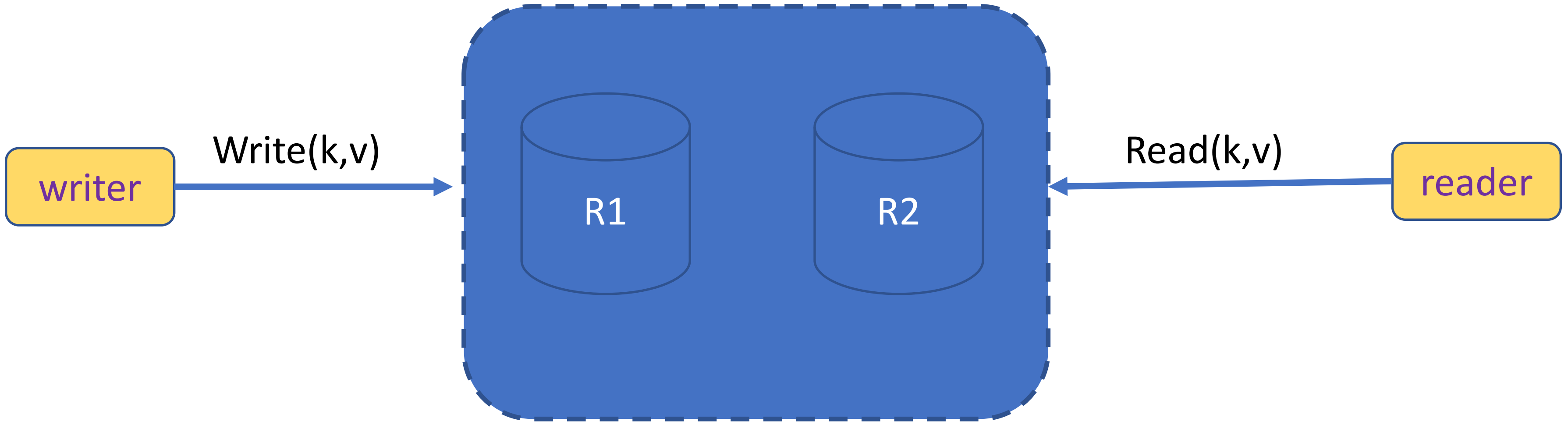
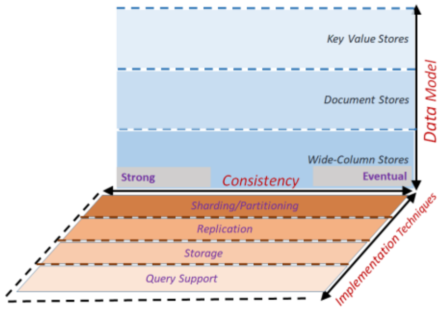
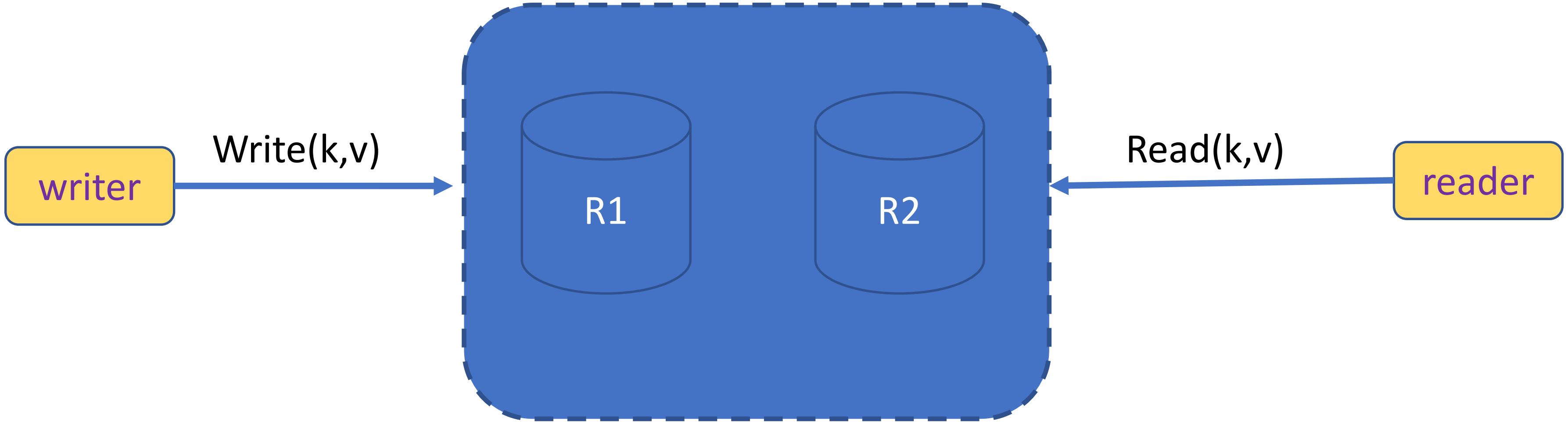


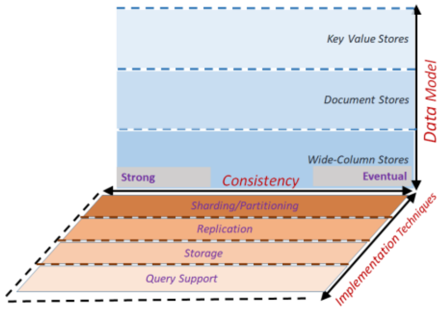
- Clients perform reads and writes



Consistency: the core problem



- Clients perform reads and writes
- Data is replicated among a set of servers



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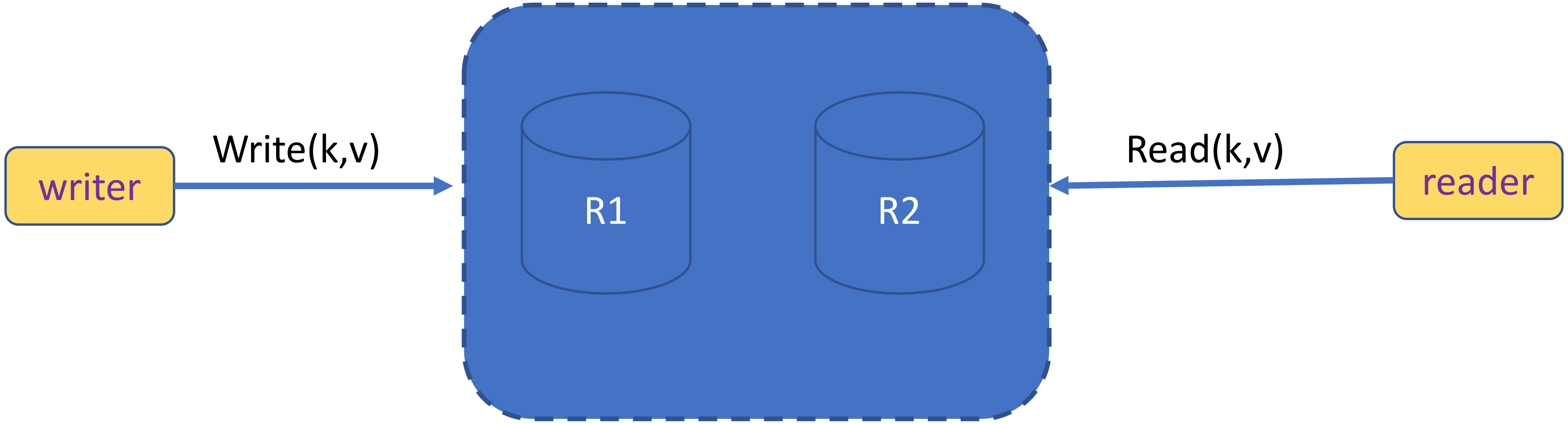
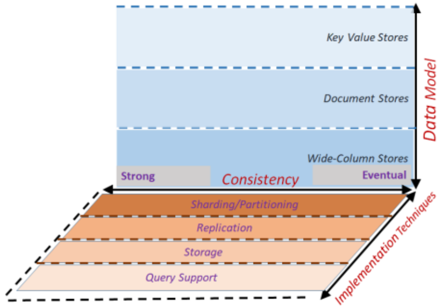


- Clients perform reads and writes
- Data is replicated among a set of servers
- Writes must be performed at all servers



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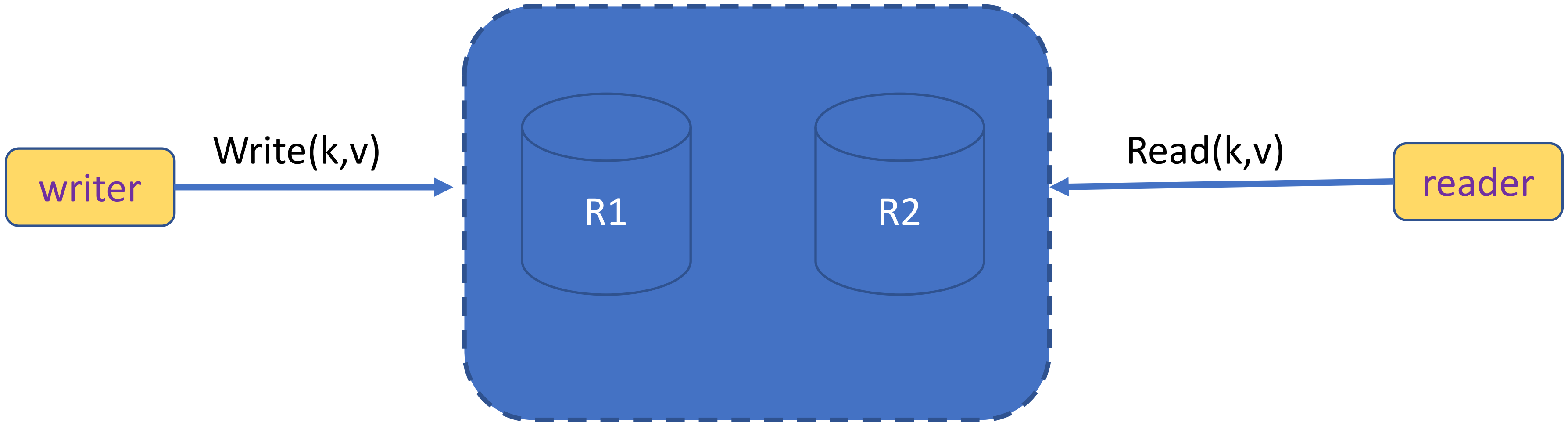
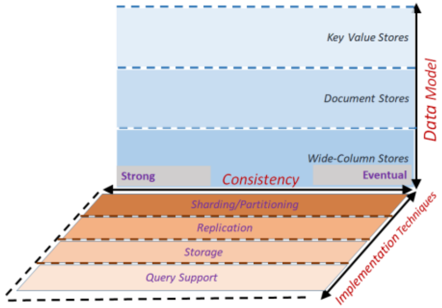
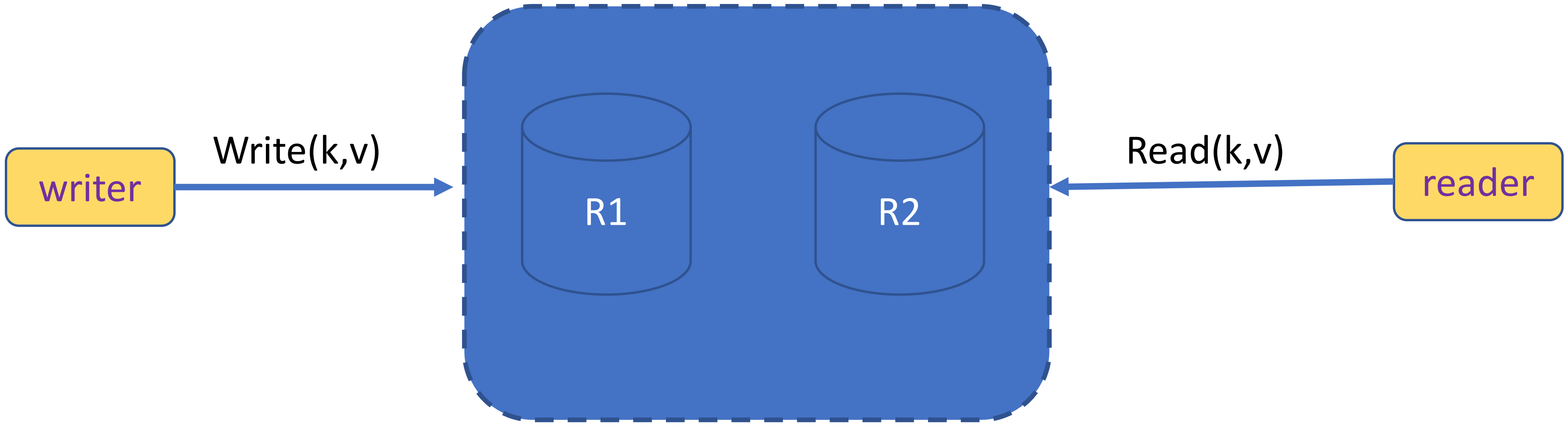


- Clients perform reads and writes
- Data is replicated among a set of servers
- Writes must be performed at all servers
- Reads return the result of one or more past writes

Consistency: the core problem





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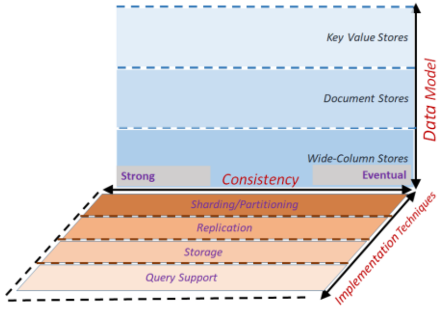
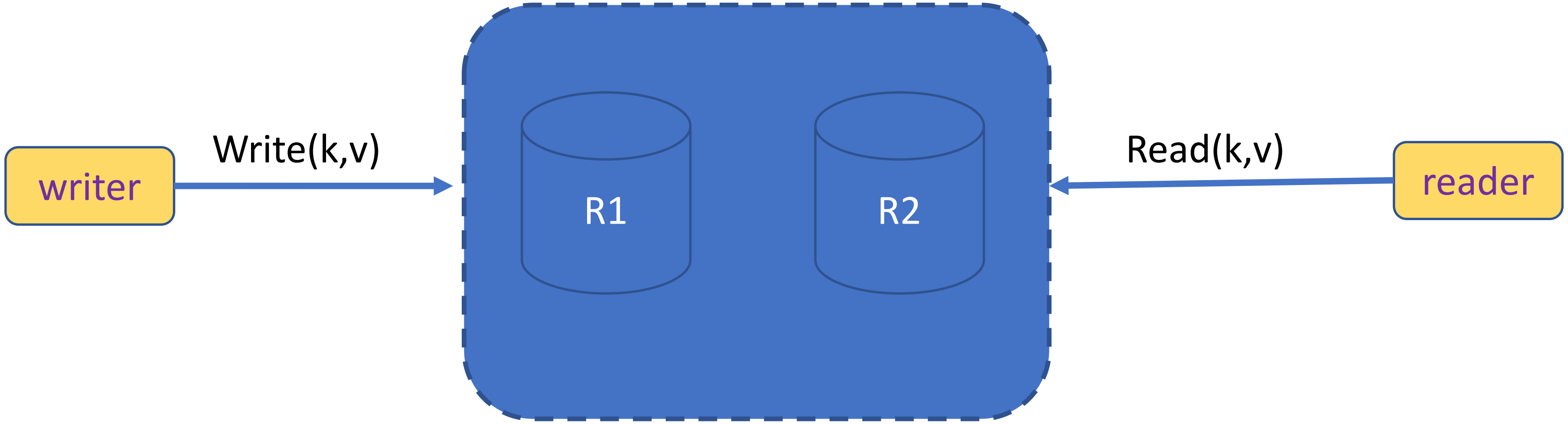
- How should we *implement* write?

Consistency: the core problem

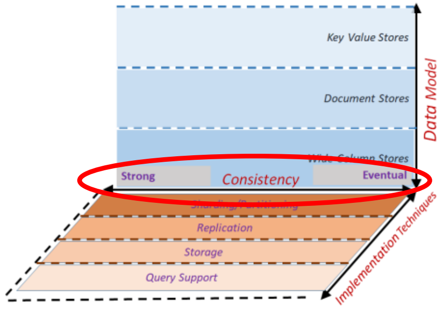




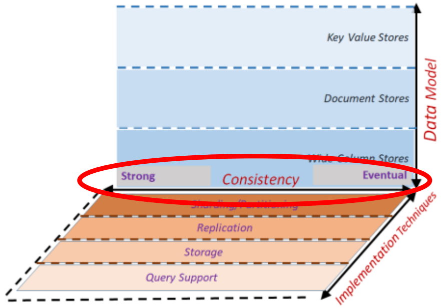
- Clients perform reads and writes
- Data is replicated among a set of servers
- Writes must be performed at all servers
- Reads return the result of one or more past writes

- How should we *implement* write?
- How to *implement* read?

Consistency: CAP Theorem

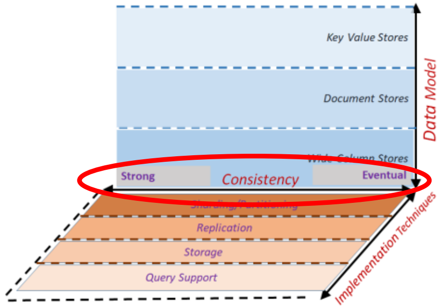


Consistency: CAP Theorem



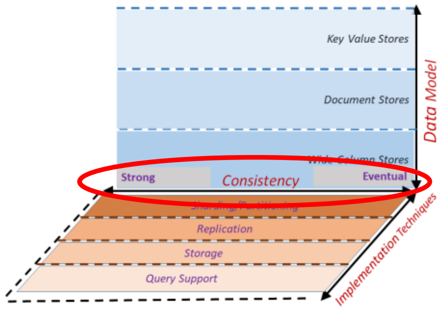
- A distributed system can satisfy at most 2/3 guarantees of:

Consistency: CAP Theorem



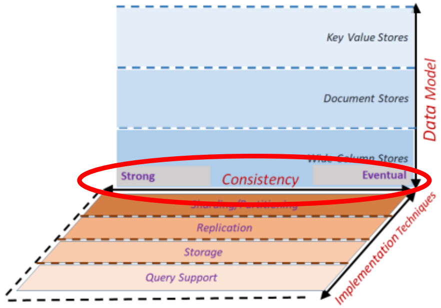
- A distributed system can satisfy at most 2/3 guarantees of:
    1. **Consistency**:

Consistency: CAP Theorem



- A distributed system can satisfy at most 2/3 guarantees of:
  1. **Consistency**:
     - all nodes see same data at any time
     - or reads return latest written value by any client

Consistency: CAP Theorem



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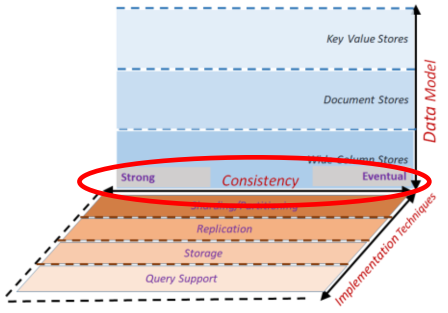
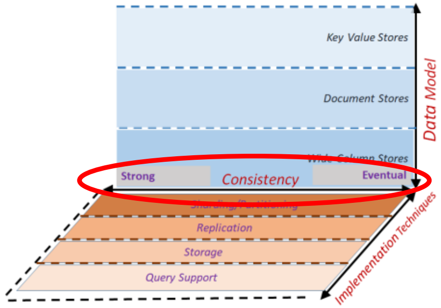
  2. **Availability**:



Consistency: CAP Theorem

- A distributed system can satisfy at most 2/3 guarantees of:
  1. **Consistency**:
     - all nodes see same data at any time
     - or reads return latest written value by any client
  2. **Availability**:
     - system allows operations all the time,
     - and operations return quickly

Consistency: CAP Theorem



- A distributed system can satisfy at most 2/3 guarantees of:
  1. **Consistency**:
     - all nodes see same data at any time
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  2. **Availability**:
     - system allows operations all the time,
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  3. **Partition-tolerance**:

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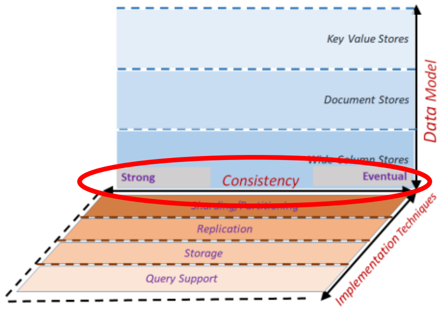

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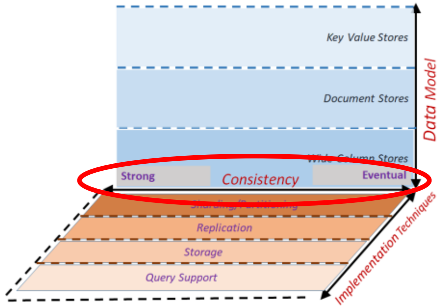
        - system continues to work in spite of network partitions

Consistency: CAP Theorem



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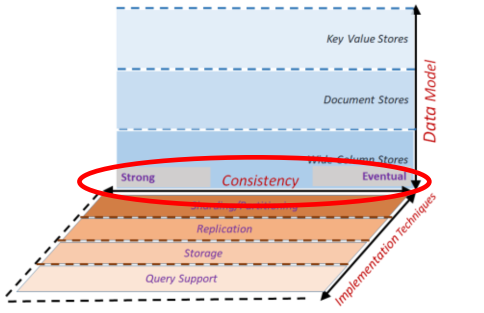

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Why care about CAP Properties?

Availability

- Reads/writes complete reliably and quickly.
- E.g. Amazon, each ms latency → $6M yearly loss.

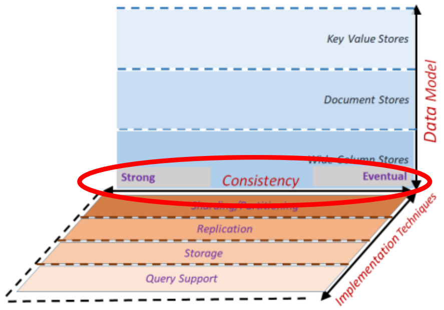
Partitions

- Internet router outages
- Under-sea cables cut
- rack switch outage
- *system should continue functioning normally!*

Consistency

- all nodes see same data at any time, or reads return latest written value by any client.
- ***This basically means correctness!***

Consistency: CAP Theorem



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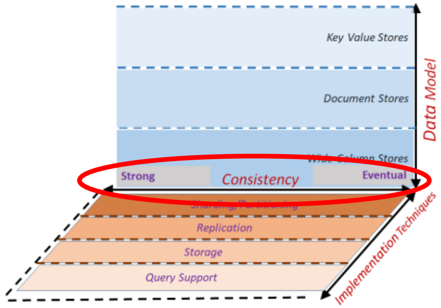

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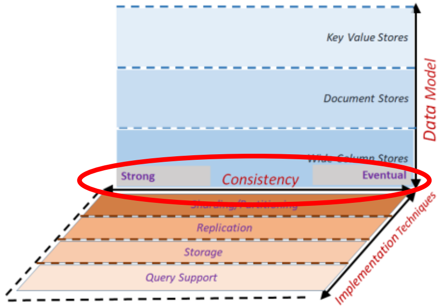

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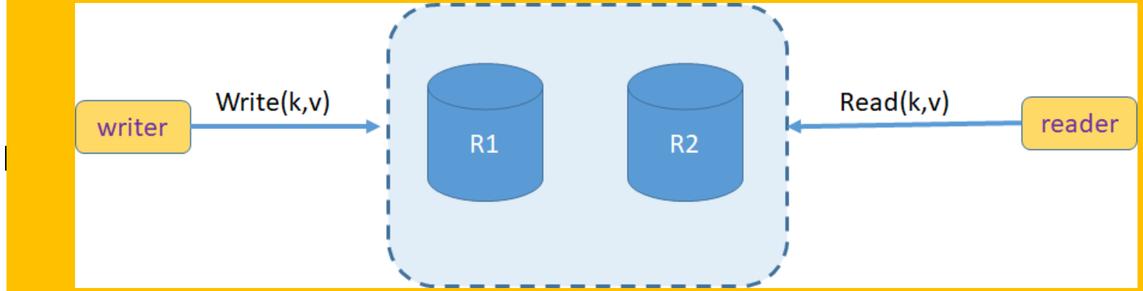

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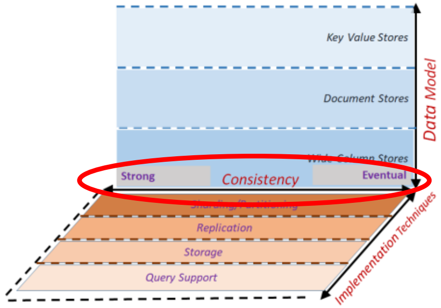

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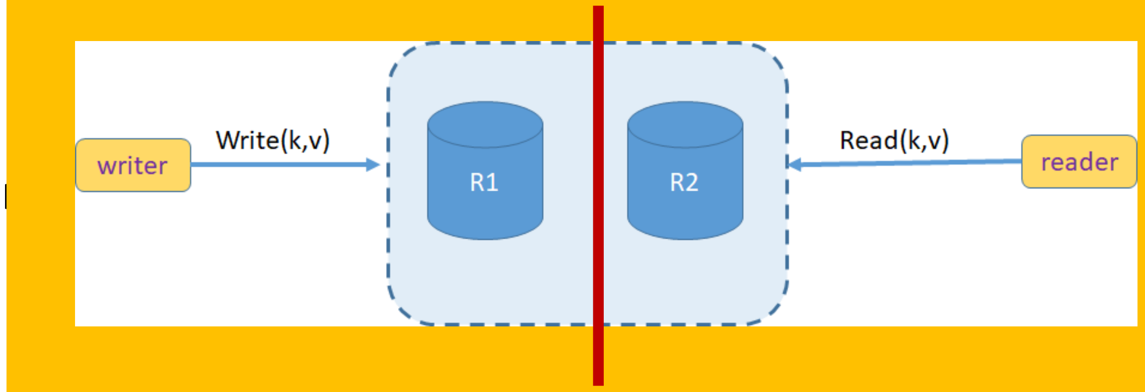

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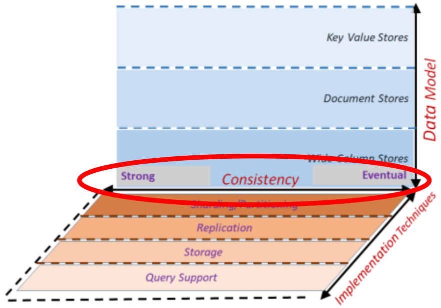

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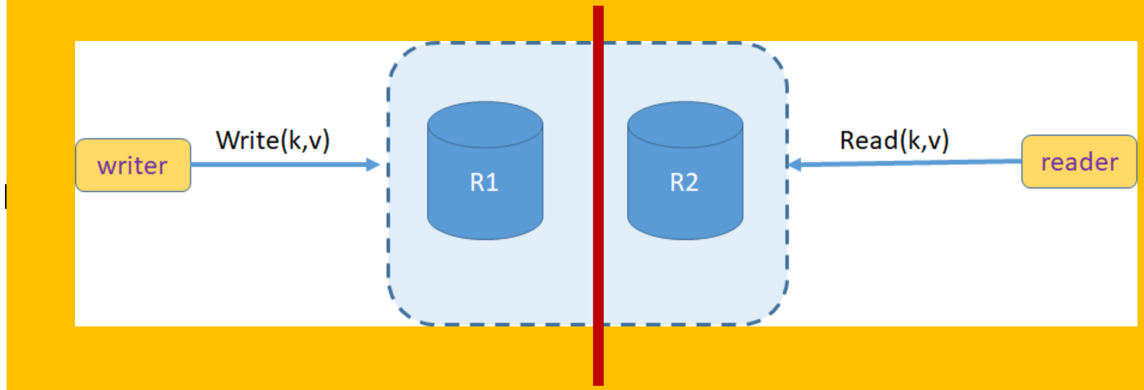
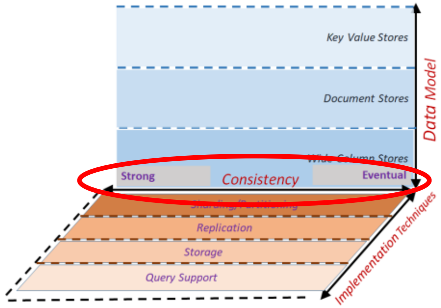


if(partition) { keep going } → !consistent && available



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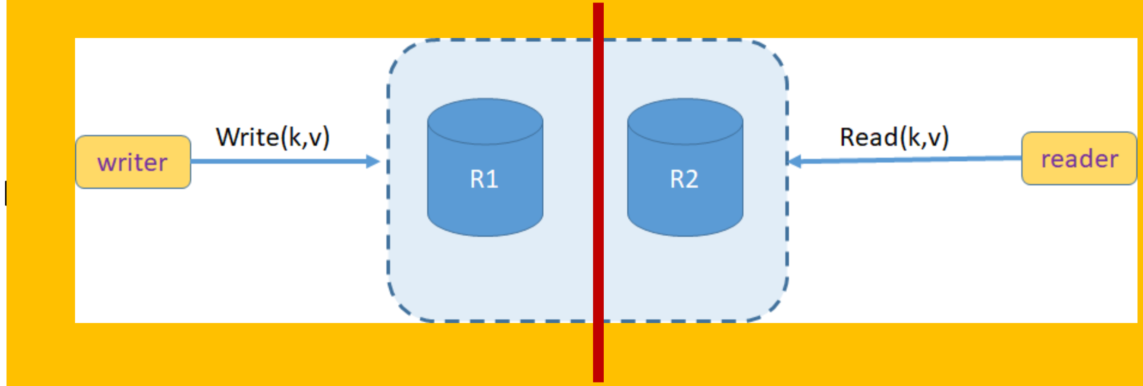
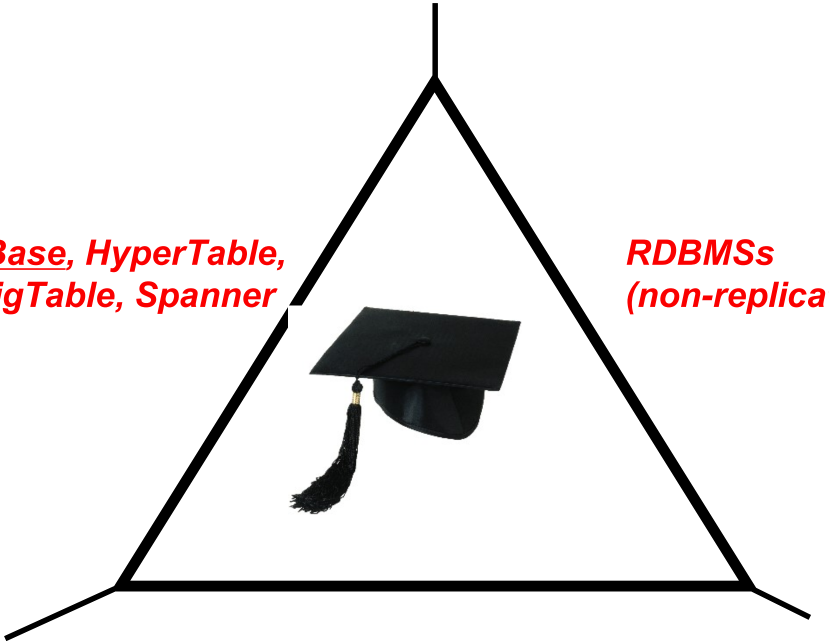


if(partition) { keep going } → !consistent && available
if(partition) { stop } → consistent && !available

CAP Implications

- A distributed storage system can achieve at most two of C, A, and P.
- When partition-tolerance is important, you have to choose between consistency and availability



Consistency

HBase, HyperTable, BigTable, Spanner

RDBMSs (non-replicated)

Partition-tolerance

Availability

Cassandra, RIAK, Dynamo, Voldemort

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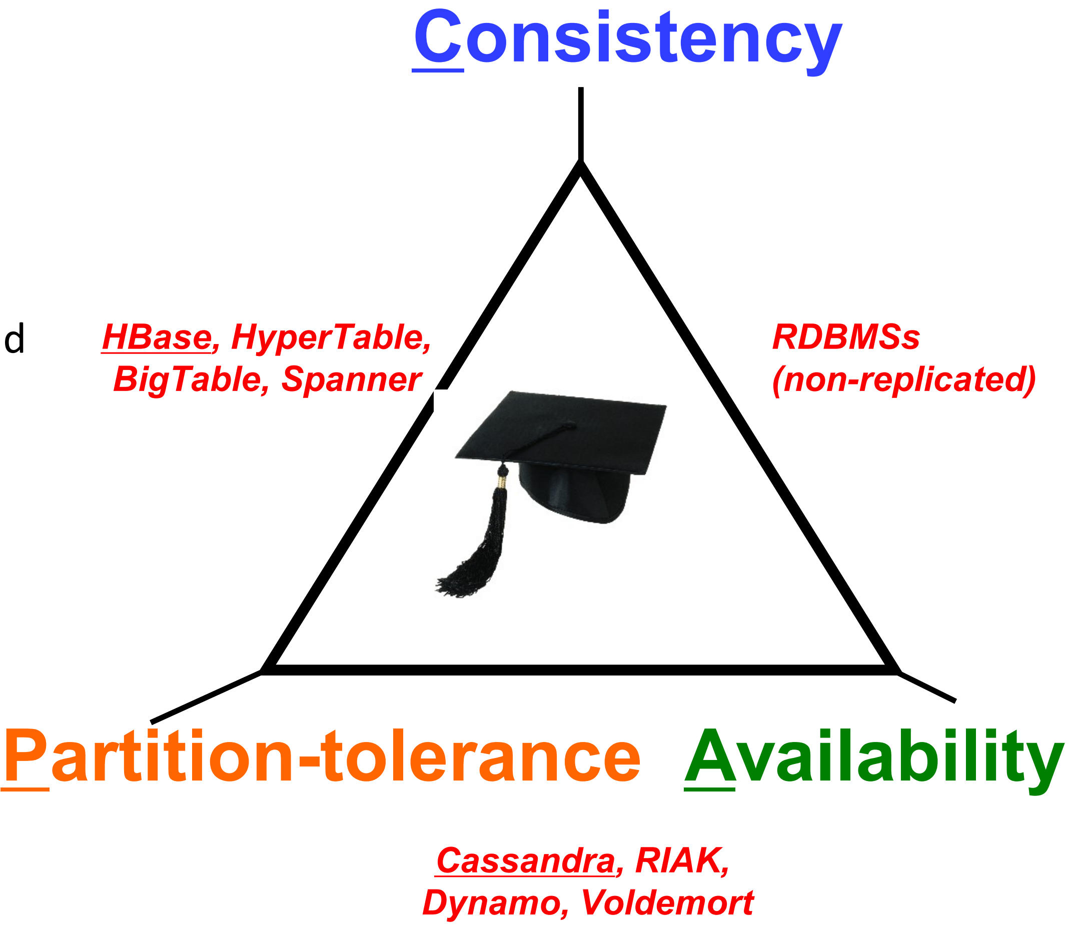
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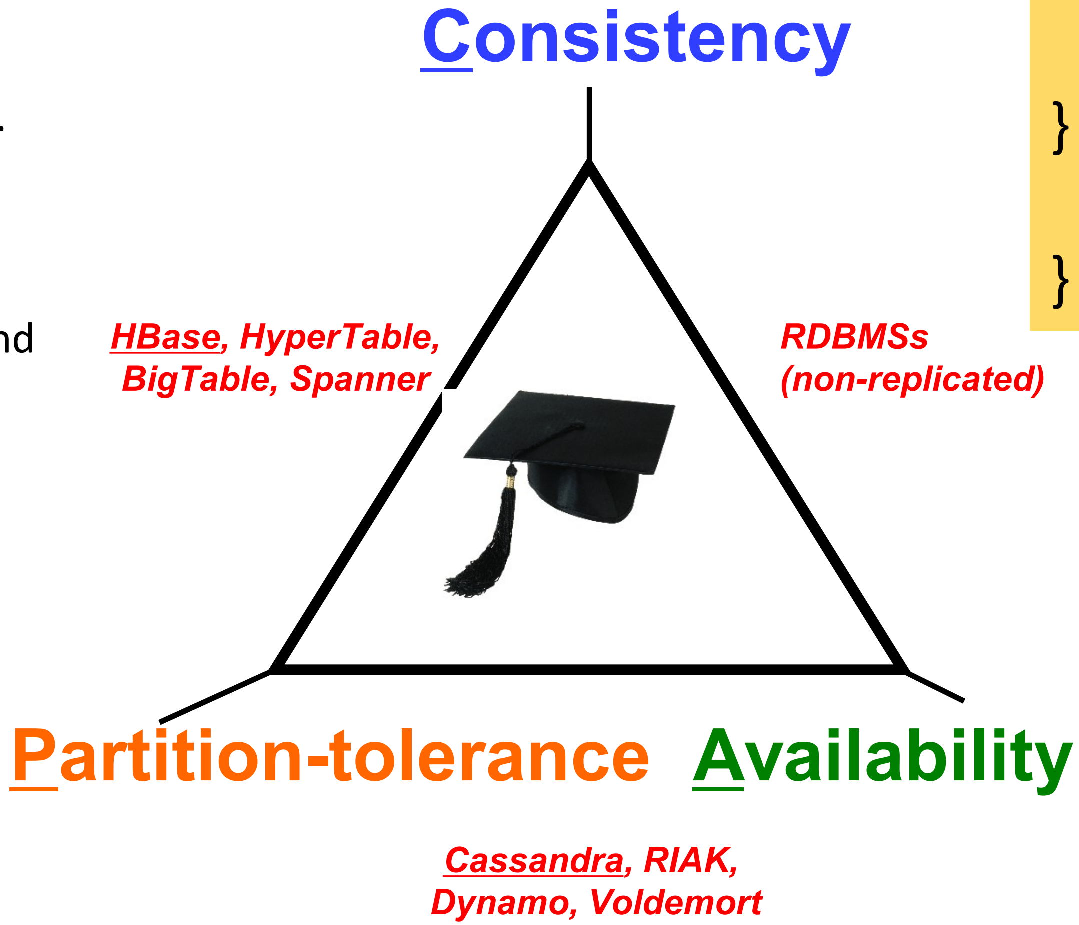

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RDBMSs (non-replicated)

Partition-tolerance

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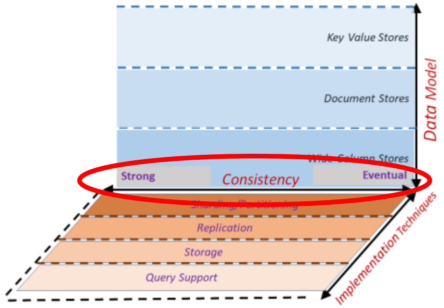
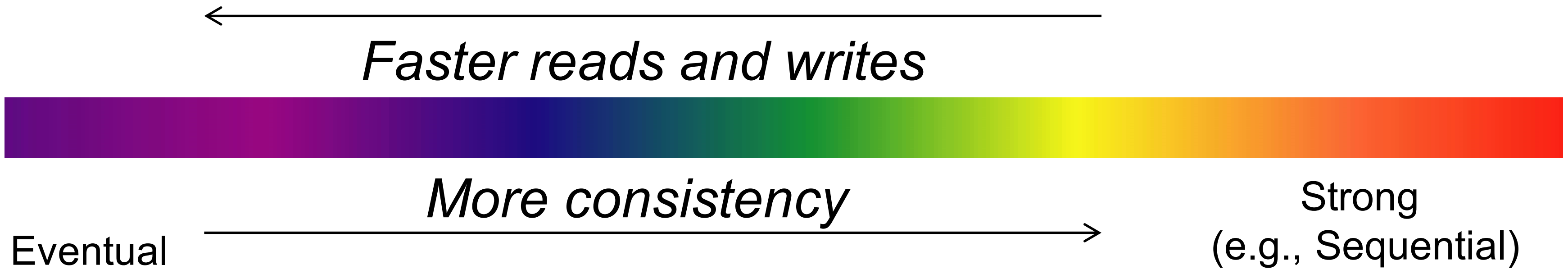
PACELC:

```
if(partition) {
    choose A or C
} else {
    choose latency or consistency
}
```

Consistency Spectrum



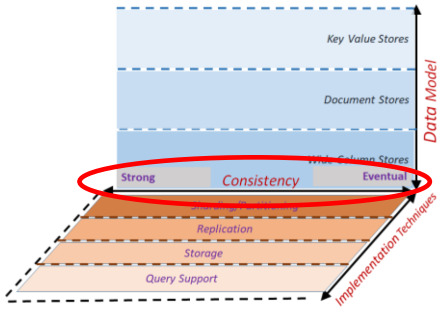

Faster reads and writes

More consistency

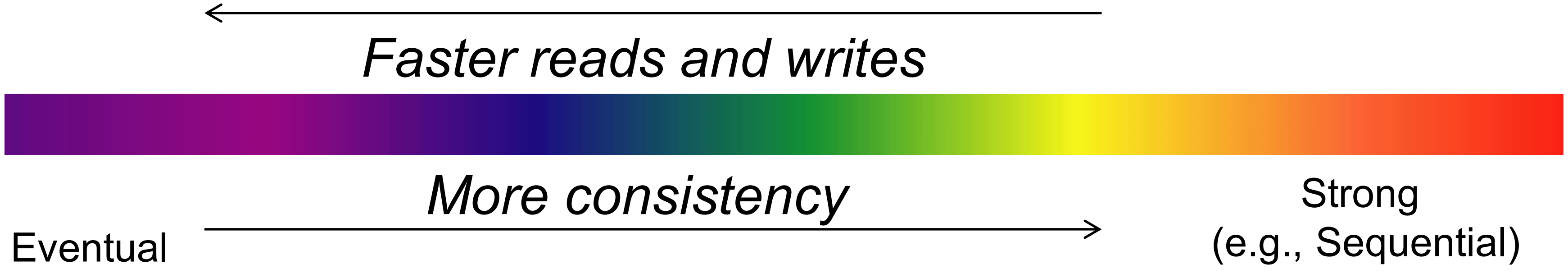
Eventual

Strong
(e.g., Sequential)

Spectrum Ends: Eventual Consistency



- Eventual Consistency
  - If writes to a key stop, all replicas of key will converge
  - Originally from Amazon’s Dynamo and LinkedIn’s Voldemort systems



Faster reads and writes

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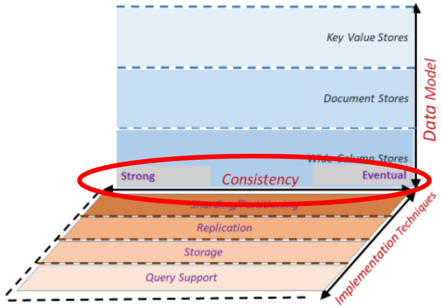
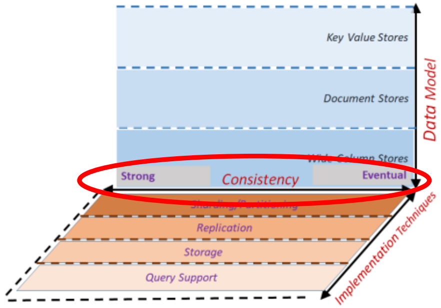
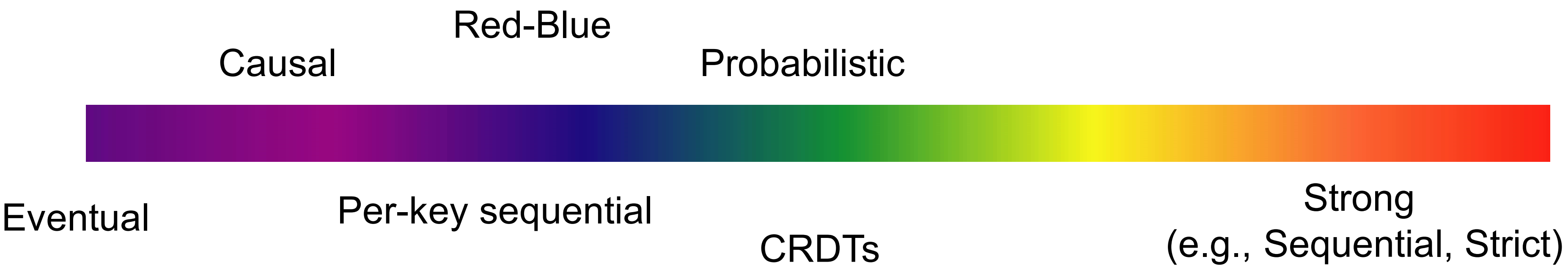
Spectrum Ends: Strong Consistency



- **Strict:**
  - Absolute time ordering of all shared accesses, reads always return last write
- **Linearizability**:
  - Each operation is visible (or available) to all other clients in real-time order
- **Sequential Consistency** [Lamport]:
  - *"... the result of any execution is the same as if the operations of all the processors were executed in some sequential order, and the operations of each individual processor appear in this sequence in the order specified by its program.*
  - After the fact, find a "reasonable" ordering of the operations (can re-order operations) that obeys sanity (consistency) at all clients, and across clients.
- **ACID** properties



Many *Many* Consistency Models



Red-Blue

Causal

Probabilistic

Eventual

Per-key sequential

CRDTs

Strong
(e.g., Sequential, Strict)

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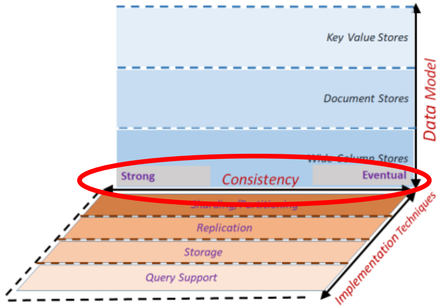

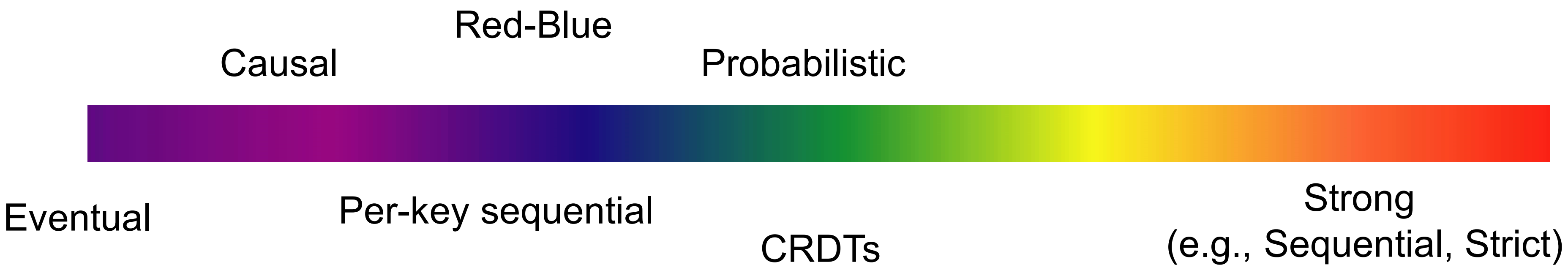

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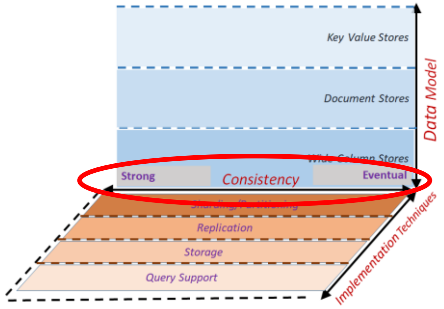
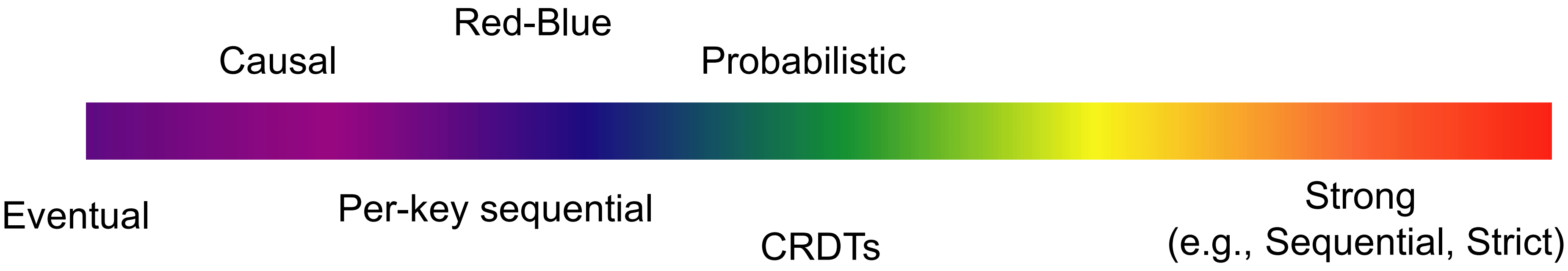
- Amazon S3 – **eventual** consistency
- Amazon Simple DB – **eventual** or strong
- Google App Engine – **strong** or eventual
- Yahoo! PNUTS – **eventual** or strong
- Windows Azure Storage – **strong** (or eventual)
- Cassandra – **eventual** or strong (if R+W > N)
- ...

Many *Many* Consistency Models

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Question: How to choose what to use or support?

Some Consistency Guarantees

Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
Consistent Prefix	See initial sequence of writes.
Bounded Staleness	See all “old” writes.
Monotonic Reads	See increasing subset of writes.
Read My Writes	See all writes performed by reader.

Some Consistency Guarantees

		consistency	performance	availability
Strong Consistency	See all previous writes.	A	D	F
Eventual Consistency	See subset of previous writes.	D	A	A
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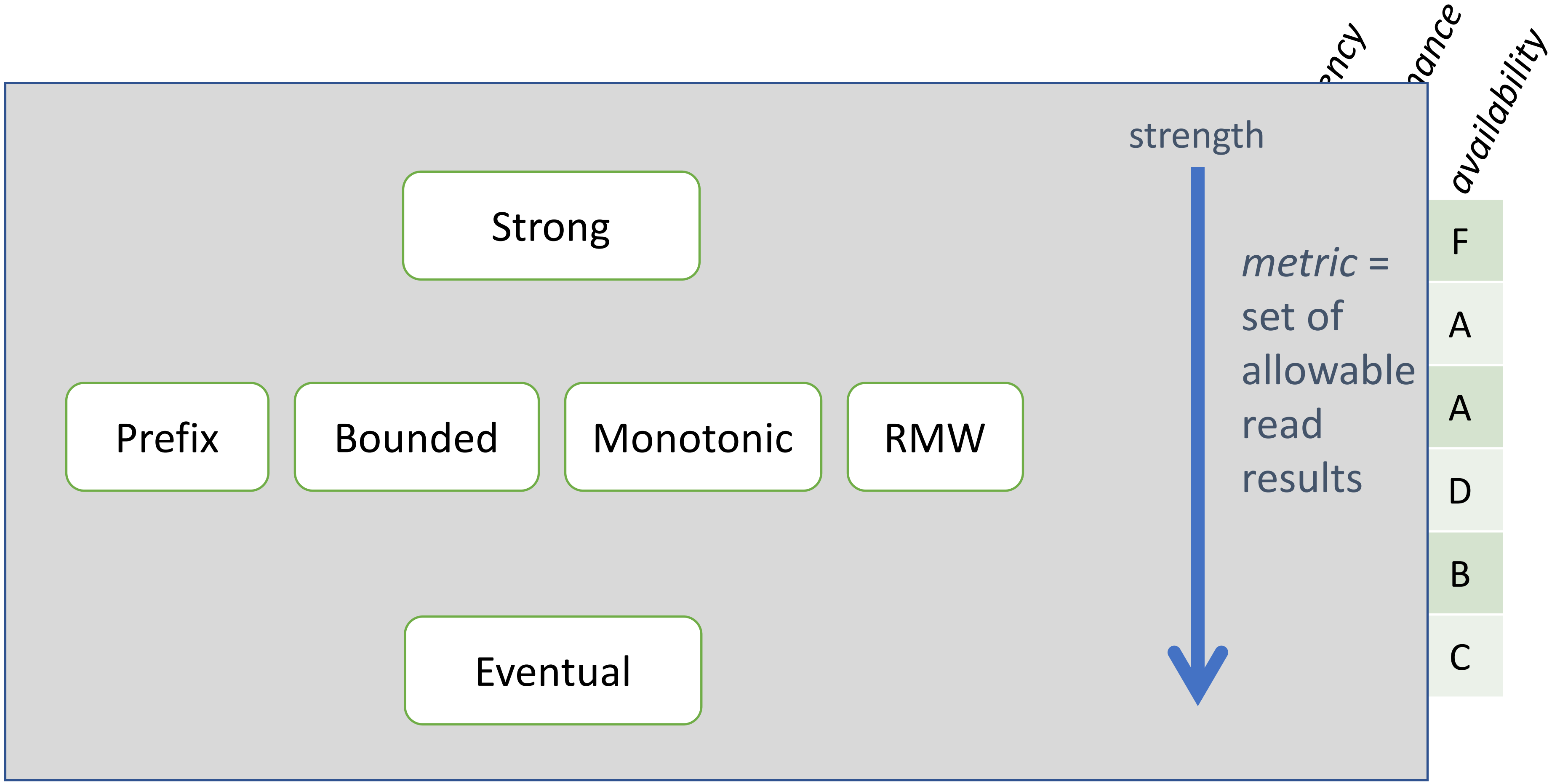

The Game of Soccer

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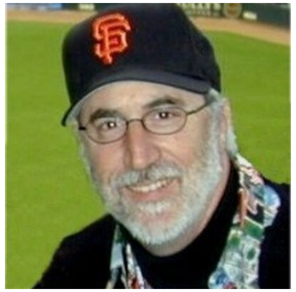

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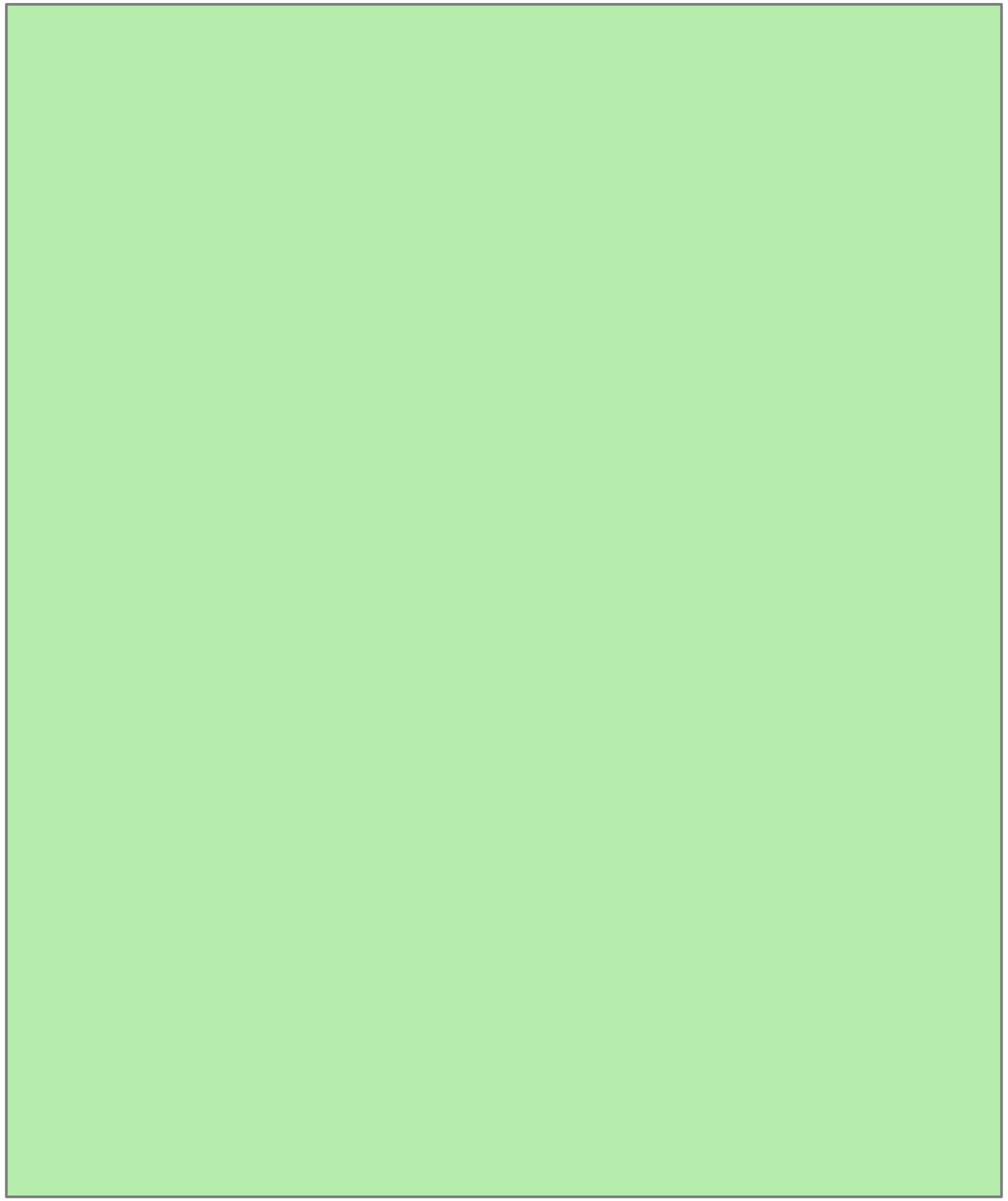

The Game of Soccer

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for half = 1 .. 2  {
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The Game of Soccer

```
for half = 1 .. 2  {
  while half not over {
```

The Game of Soccer

```
for half = 1 .. 2  {
  while half not over {
      kick-the-ball-at-the-goal
```

The Game of Soccer

```
for half = 1 .. 2  {
  while half not over {
      kick-the-ball-at-the-goal
      for each goal {
```

The Game of Soccer

```
for half = 1 .. 2  {
  while half not over {
      kick-the-ball-at-the-goal
      for each goal {
        if visiting-team-scored {
```

The Game of Soccer

```
for half = 1 .. 2  {
  while half not over {
      kick-the-ball-at-the-goal
      for each goal {
       if visiting-team-scored {
         score = Read (“visitors”);
```

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for half = 1 .. 2  {
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if (hScore == vScore)
```

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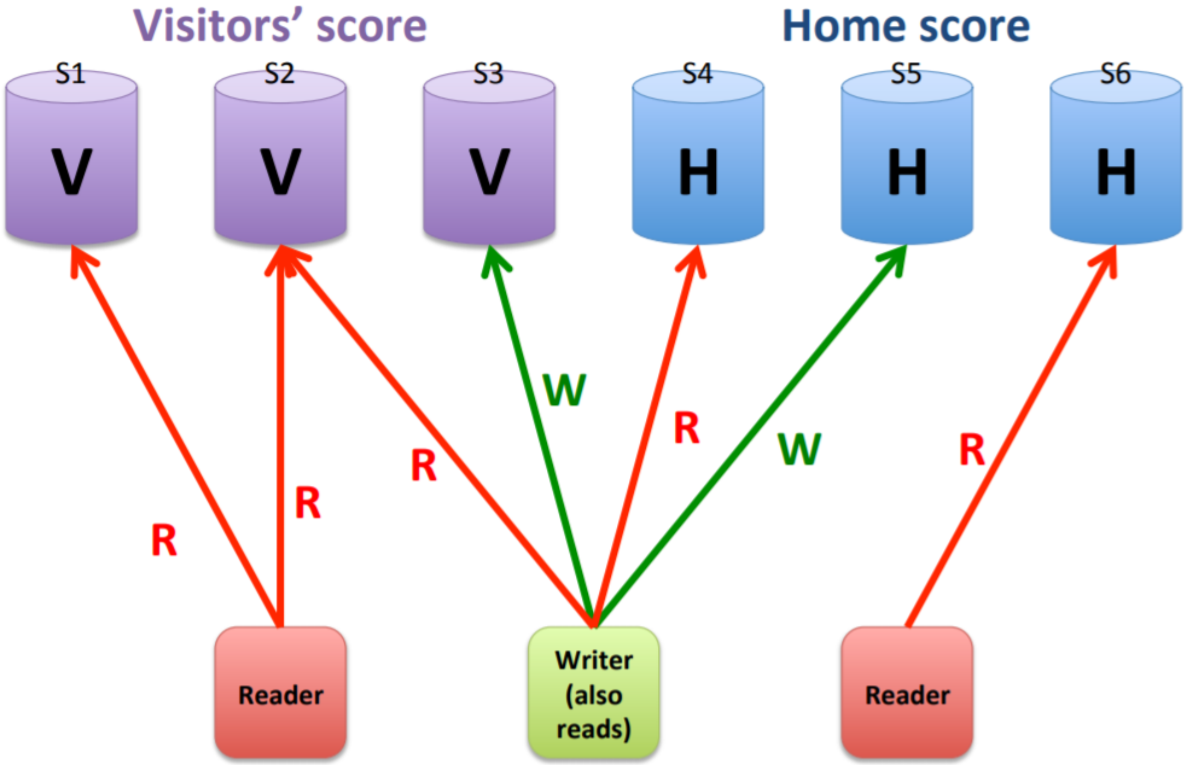

Official Scorekeeper

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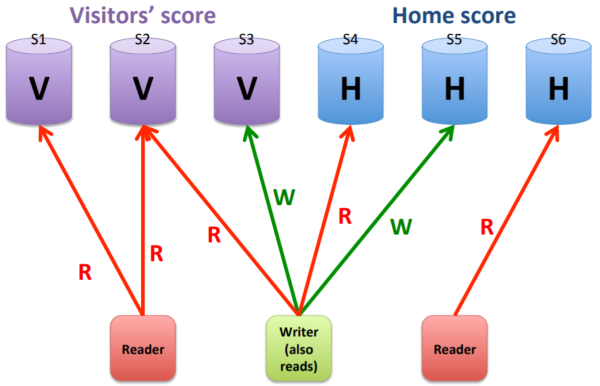

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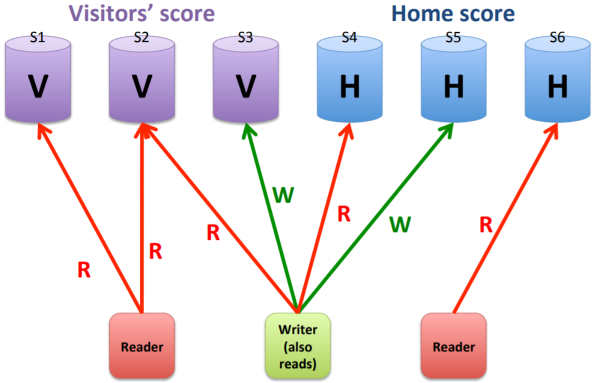

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Desired consistency?

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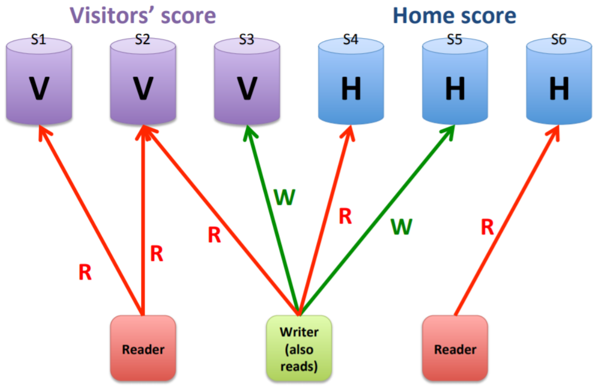

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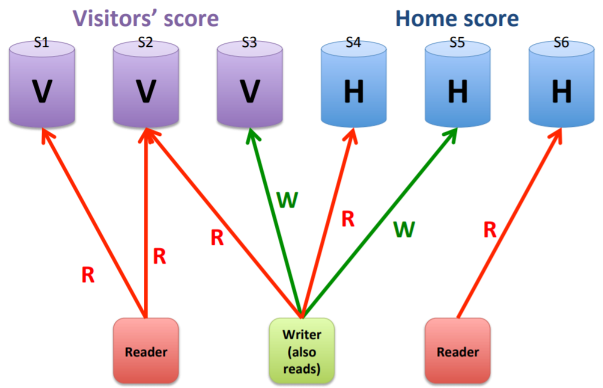

```
score = Read ("visitors");
Write ("visitors", score + 1);
```

Desired consistency?

Strong

= Read My Writes!

Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
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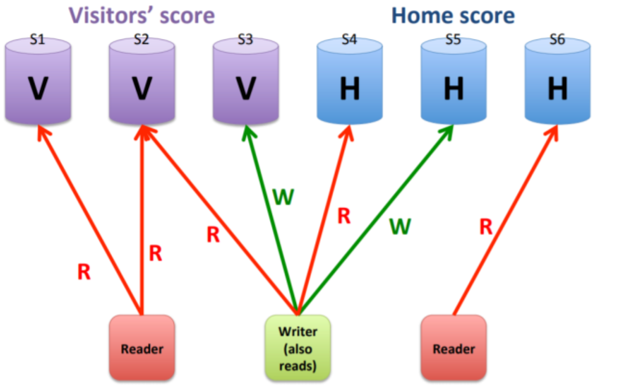
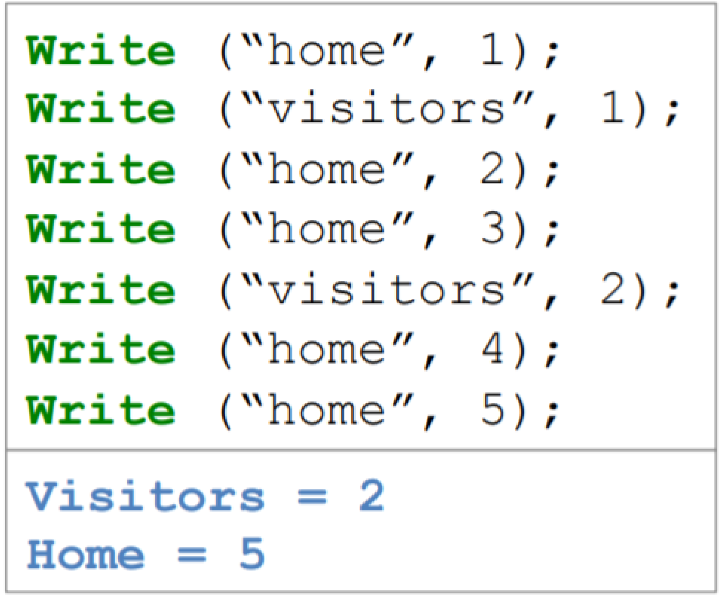


score = **Read** ("visitors");

Write ("visitors", score + 1);



```
Write ("home", 1);
Write ("visitors", 1);
Write ("home", 2);
Write ("home", 3);
Write ("visitors", 2);
Write ("home", 4);
Write ("home", 5);
```

```
Visitors = 2
Home = 5
```

Desired consistency?

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= Read My Writes!

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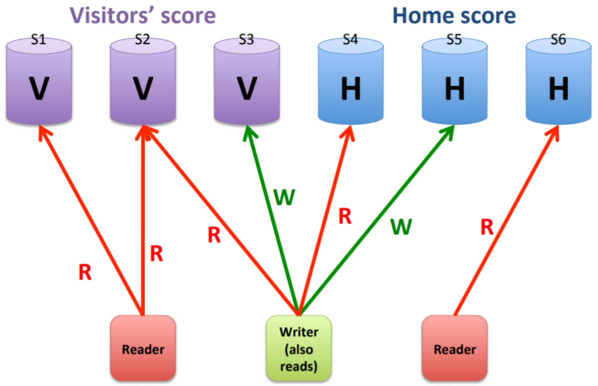
Referee



```
vScore = Read (“visitors”);
hScore = Read (“home”);
if vScore == hScore
    play-overtime
```

Strong Consistency	See all previous writes.
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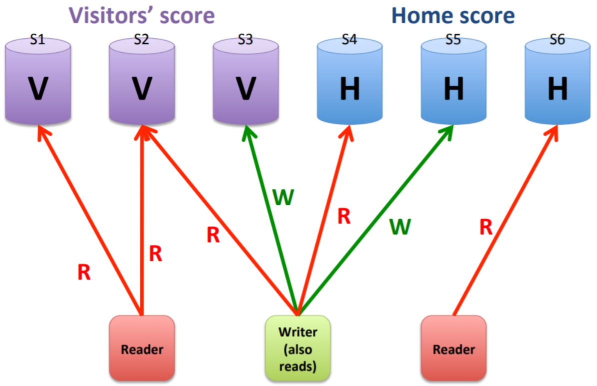

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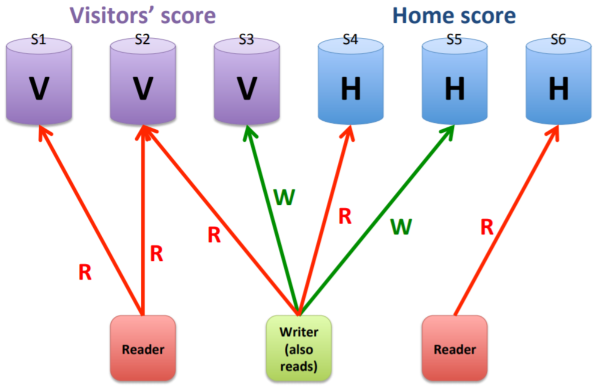

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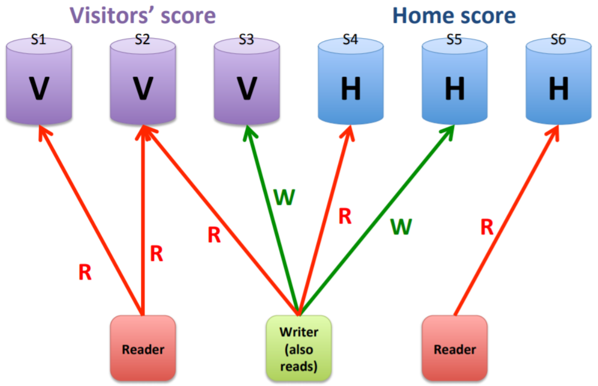

Radio Reporter

```
do {
    BeginTx();
        vScore = Read ("visitors");
        hScore = Read ("home");
    EndTx();
    report vScore and hScore;
    sleep (30 minutes);
}
```

Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
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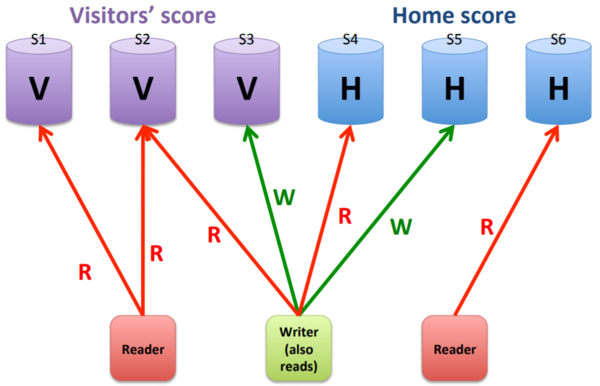

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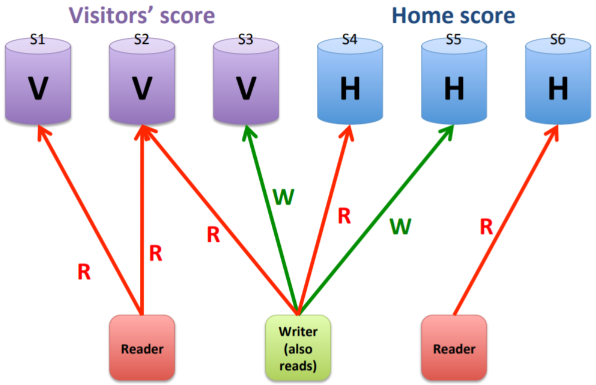

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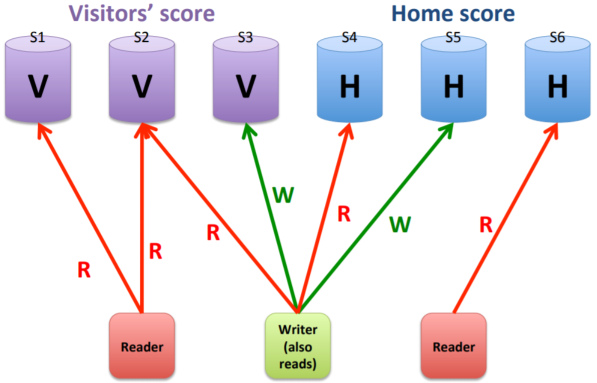

Radio Reporter

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Consistent Prefix

Monotonic Reads

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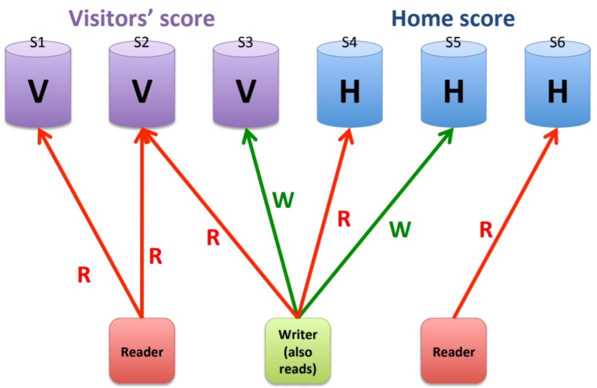

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Desired consistency?

Consistent Prefix

Monotonic Reads

or Bounded Staleness

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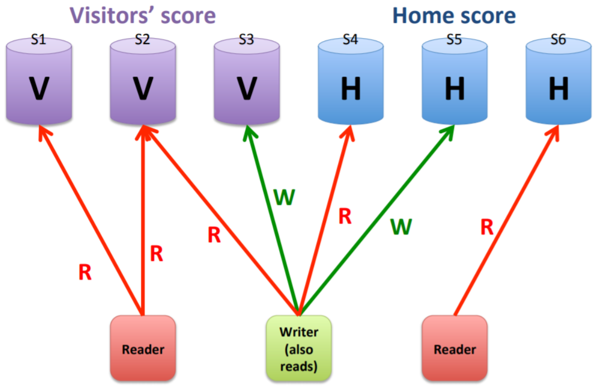
Sportswriter



```
 While not end of game {
     drink beer;
     smoke cigar;
}
go out to dinner;
vScore = Read ("visitors");
hScore = Read ("home");
write article;
```

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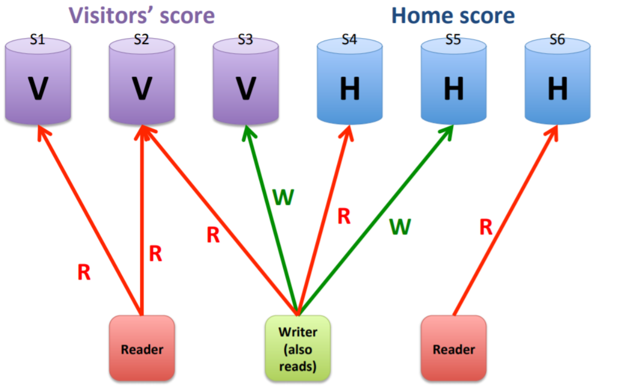

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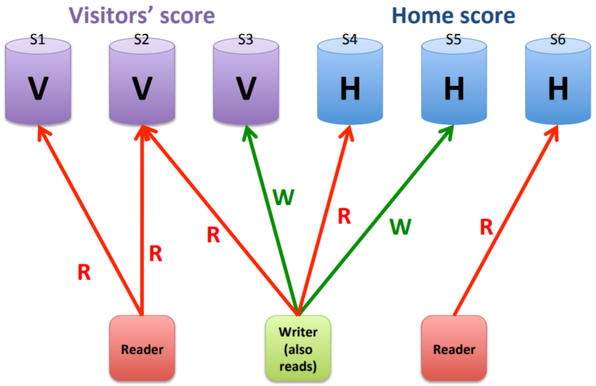

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```

Desired consistency?

Eventual

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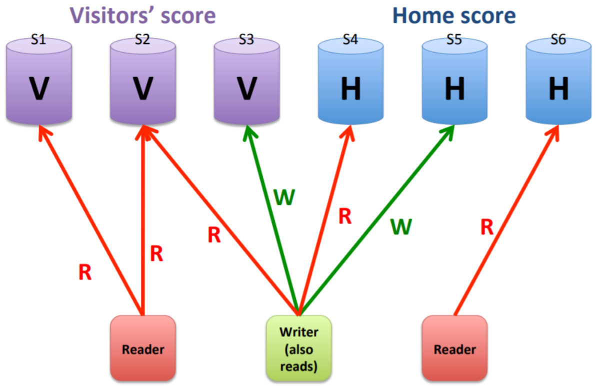
Sportswriter



```
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}
go out to dinner;
vScore = Read (“visitors”);
hScore = Read (“home”);
write article;
```

Desired consistency?

Eventual

Bounded Staleness

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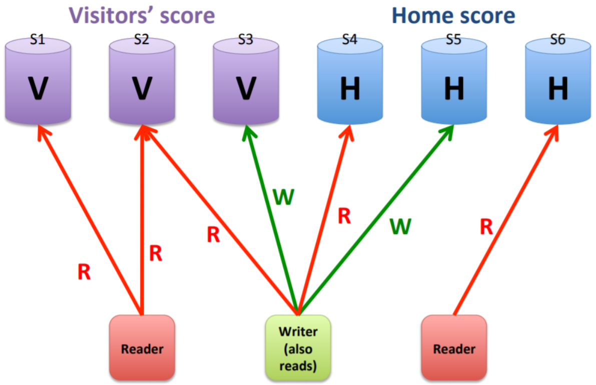
Statistician



```
Wait for end of game;
score = Read ("home");
stat = Read ("season-goals");
Write ("season-goals", stat + score);
```

Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
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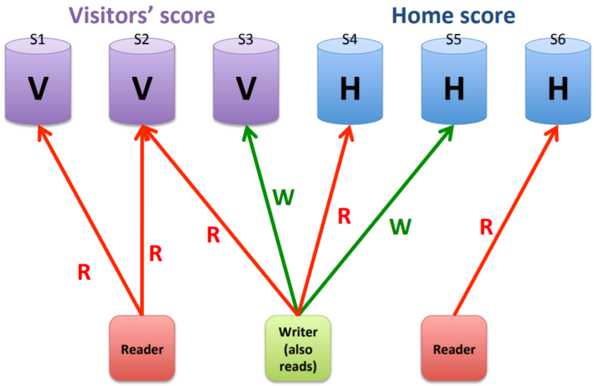

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```
Wait for end of game;
score = **Read** ("home");
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**Write** ("season-goals", stat + score);
```

Desired consistency?

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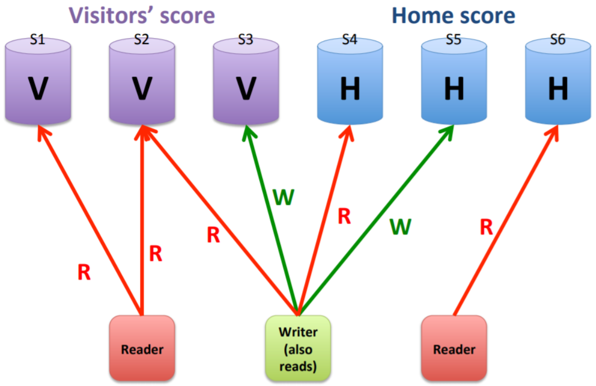

```
Wait for end of game;
score = Read (“home”);
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Write (“season-goals”, stat + score);
```

Desired consistency?

Strong Consistency (1st read)

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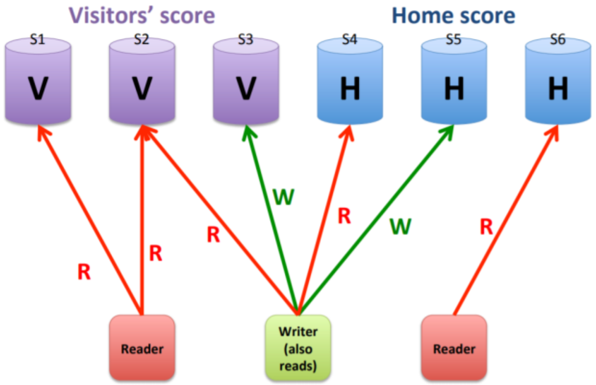

```
Wait for end of game;
score = Read ("home");
stat = Read ("season-goals");
Write ("season-goals", stat + score);
```

Desired consistency?

Strong Consistency (1st read)

Read My Writes (2nd read)

Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
Consistent Prefix	See initial sequence of writes.
Monotonic Reads	See increasing subset of writes.
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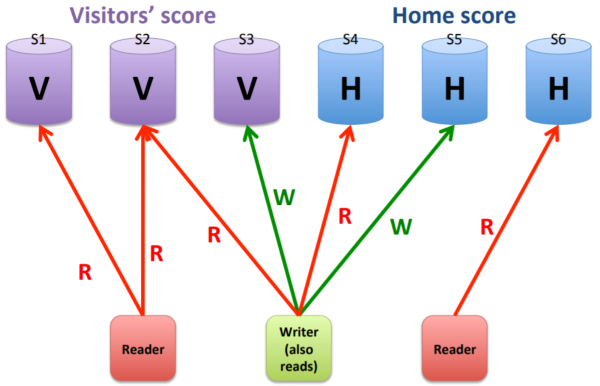
Stat Watcher



```
do {
      stat = Read (“season-goals”);
      discuss stats with friends;
      sleep (1 day);
}
```

Strong Consistency	See all previous writes.
Eventual Consistency	See subset of previous writes.
Consistent Prefix	See initial sequence of writes.
Monotonic Reads	See increasing subset of writes.
Read My Writes	See all writes performed by reader.
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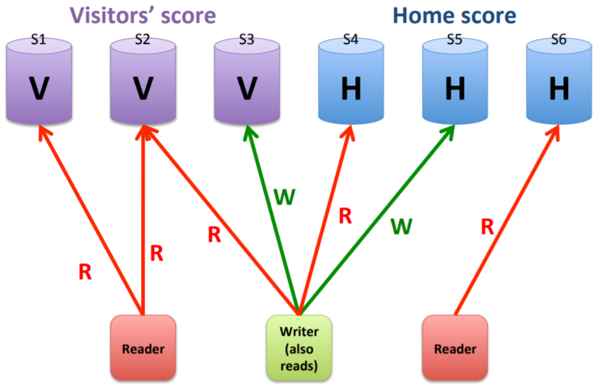

Stat Watcher

```
do {
        stat = Read ("season-goals");
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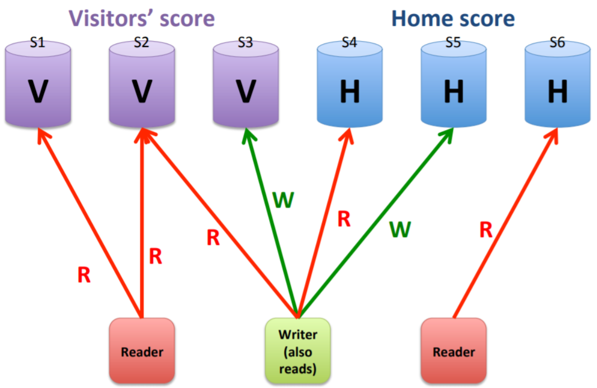

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Official scorekeeper:

```
score = Read ("visitors");
Write ("visitors"
```

Read My Writes

Referee:

Strong Consistency

Radio reporter:

```
do {
    vScore = Read ("visitors");
    hScore = Read ("home");
    report vScore and hSc
    sleep (30 minutes)
}
```

Consistent Prefix

Monotonic Reads

Sportswriter:

```
 While not end of game {
     drink beer;
     smoke cigar;
}
go out to dinner;
vScore = Read ("visit
hScore = R                   );
write article;
```

Bounded Staleness

Statistician:

```
Wait for end of game;
score = Read ("home");
stat = Read ("season-goals");
Write ("season-goals", stat +
```

Strong Consistency

Read My Writes

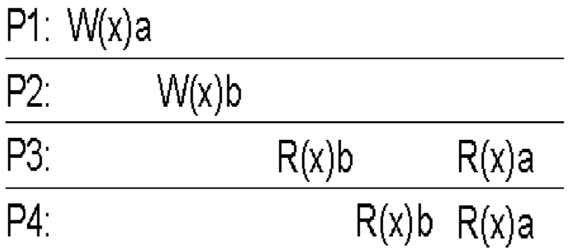
Stat watcher:

```
stat = Read ("season-runs")
discuss sta
```

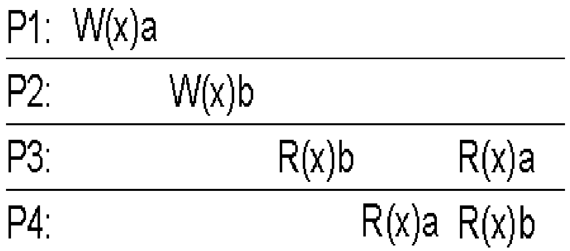
Eventual Consistency

Sequential Consistency

- weaker than strict/strong consistency
  - All operations are executed in *some* sequential order
  - each process issues operations in program order
    - Any valid interleaving is allowed
    - All agree on the same interleaving
    - Each process preserves its program order



(a)



(b)

Sequential Consistency

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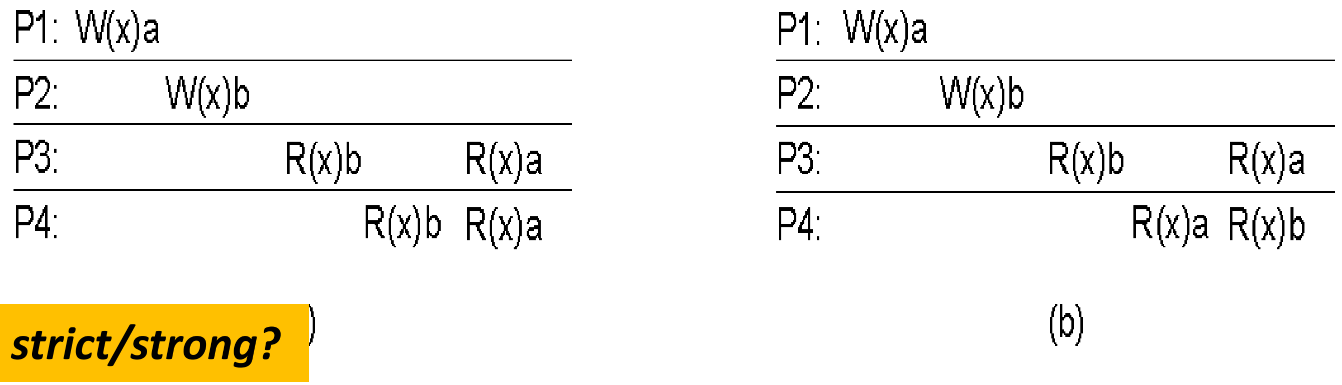

P1: W(x)a
P2: W(x)b
P3: R(x)b R(x)a
P4: R(x)b R(x)a

)

P1: W(x)a
P2: W(x)b
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P4: R(x)a R(x)b

(b)

- ***Why is this weaker than strict/strong?***

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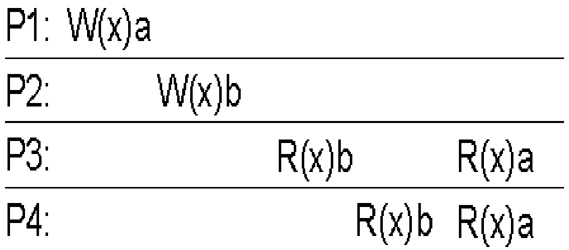

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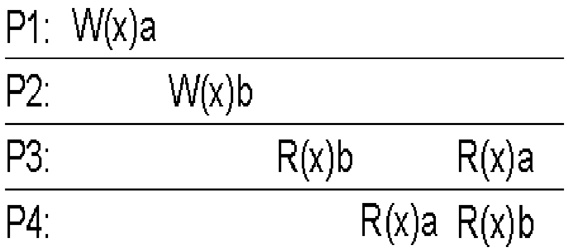

P1: W(x)a
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P3: R(x)b R(x)a
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(b)

- ***Why is this weaker than strict/strong?***
- ***Nothing is said about "most recent write"***

Linearizability

Linearizability

- Assumes sequential consistency *and*
  - If TS(x) < TS(y) then OP(x) should precede OP(y) in the sequence
  - Stronger than sequential consistency
  - Difference between linearizability and serializability?
    - Granularity: reads/writes versus transactions

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  - Stronger than sequential consistency
  - Difference between linearizability and serializability?
    - Granularity: reads/writes versus transactions
- Example:
  - Stay tuned…relevant for lock free data structures
  - Importantly: *a property of concurrent objects*

Causal consistency

Causal consistency

- Causally related writes seen by all processes in same order.

Causal consistency

- Causally related writes seen by all processes in same order.
  - *Causally?*

Causal consistency

- Causally related writes seen
  - *Causally?*

Causal:

If a write produces a value that causes another write, they are causally related

```
X = 1
if(X > 0) {
   Y = 1
}
```

Causal consistency → all see X=1, Y=1 in same order

Causal consistency

- Causally related writes seen by all processes in same order.
  - *Causally?*

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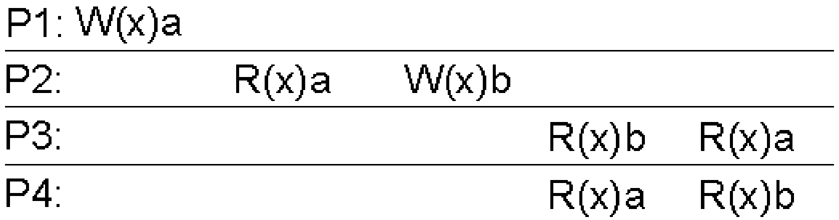

P1:	W(x)a				
P2:		R(x)a	W(x)b		
P3:				R(x)b	R(x)a
P4:				R(x)a	R(x)b

(a)

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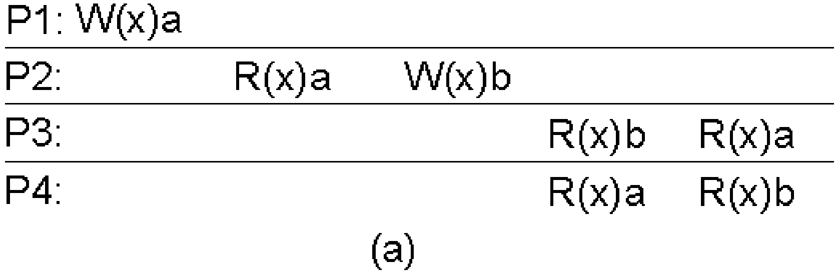

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(a)

Not permitted

Causal consistency

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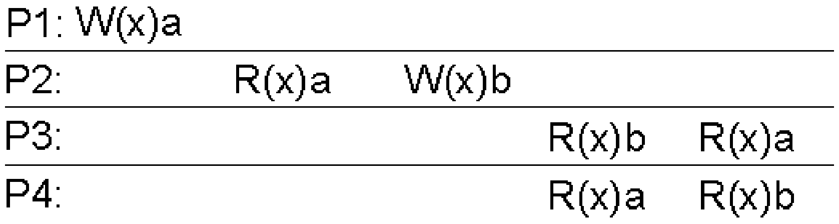

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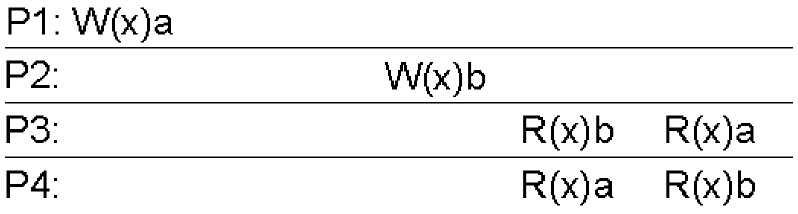
(a)



P1:	W(x)a			
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P3:			R(x)b	R(x)a
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(b)

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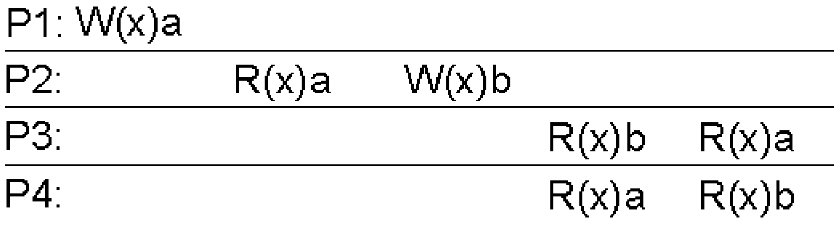
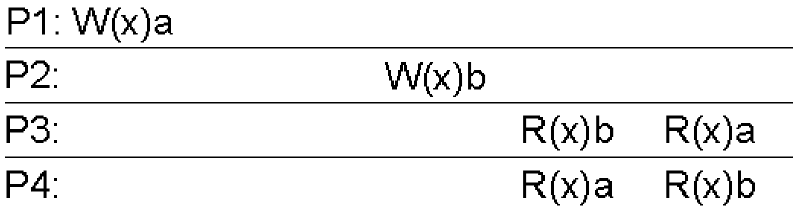
    - *Causally?*
    - *Concurrent* writes may be seen in different orders on different machines



```
P1: W(x)a
P2:           R(x)a     W(x)b
P3:                               R(x)b    R(x)a
P4:                               R(x)a    R(x)b
```

(a)

Not permitted



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P1: W(x)a
P2:                     W(x)b
P3:                               R(x)b    R(x)a
P4:                               R(x)a    R(x)b
```

(b)

Permitted

Consistency models summary

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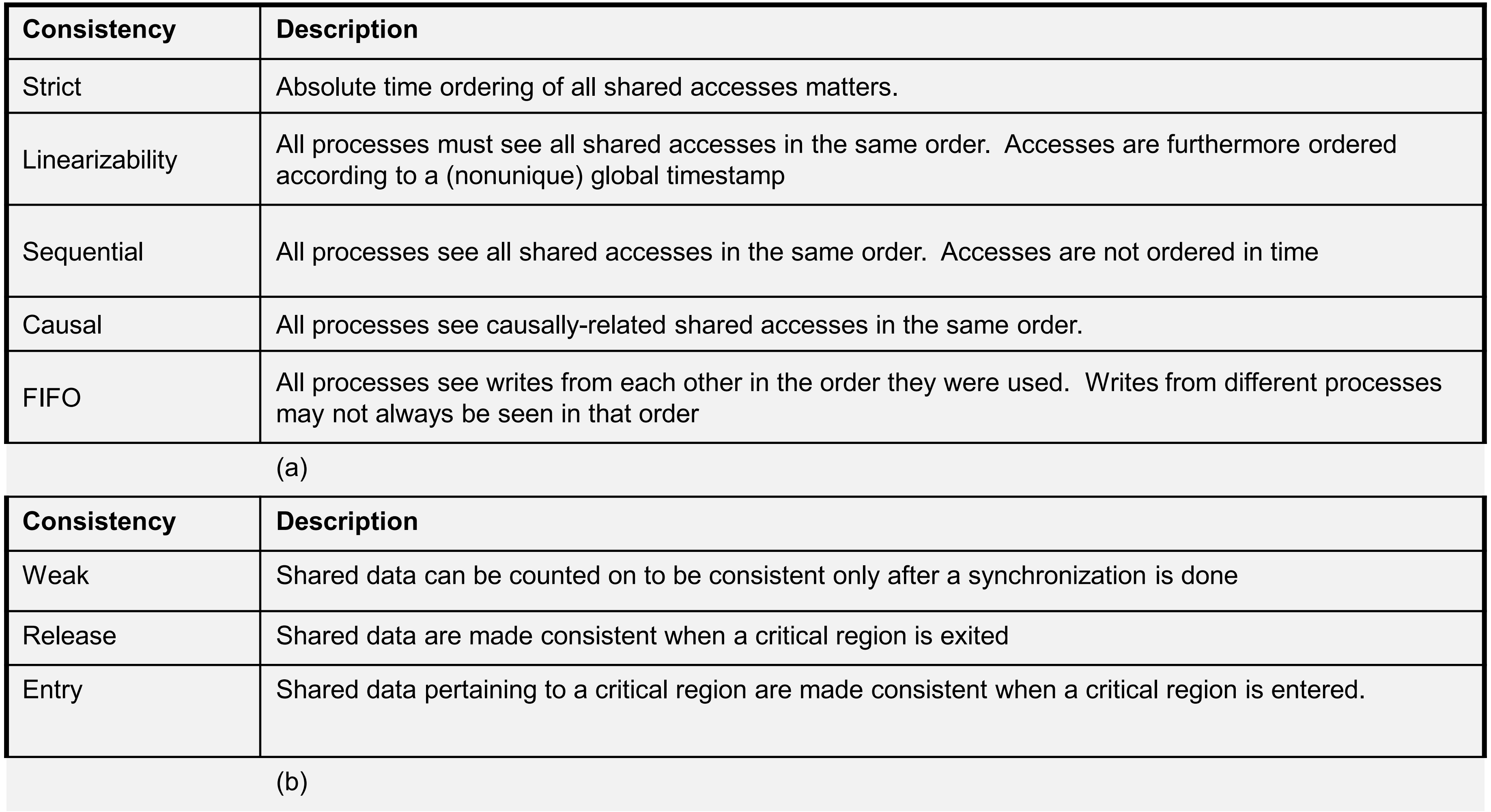

Consistency	Description
Strict	Absolute time ordering of all shared accesses matters.
Linearizability	All processes must see all shared accesses in the same order. Accesses are furthermore ordered according to a (nonunique) global timestamp
Sequential	All processes see all shared accesses in the same order. Accesses are not ordered in time
Causal	All processes see causally-related shared accesses in the same order.
FIFO	All processes see writes from each other in the order they were used. Writes from different processes may not always be seen in that order

(a)

Consistency	Description
Weak	Shared data can be counted on to be consistent only after a synchronization is done
Release	Shared data are made consistent when a critical region is exited
Entry	Shared data pertaining to a critical region are made consistent when a critical region is entered.

(b)

Non-Blocking Synchronization

Non-Blocking Synchronization

Locks: a litany of problems

Non-Blocking Synchronization

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- Deadlock

Non-Blocking Synchronization

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Solution: don’t use locks

Non-Blocking Synchronization

Locks: a litany of problems

- Deadlock
- Priority inversion
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Lock-free programming

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- Subset of a broader class: ***Non-blocking Synchronization***

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- Possible without HW support
  - e.g. Lamport’s Concurrent Buffer
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Lock-free programming

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- Built on atomic instructions like CAS + clever algorithmic tricks
- Lock-free *algorithms* are hard, so
- General approach: encapsulate lock-free algorithms in data structures
  - Queue, list, hash-table, skip list, etc.
  - New LF data structure → research result

Basic List Append

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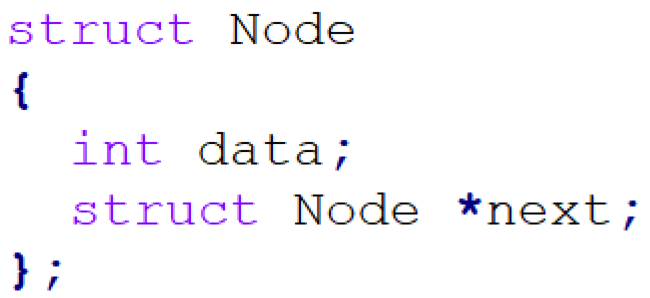

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struct Node
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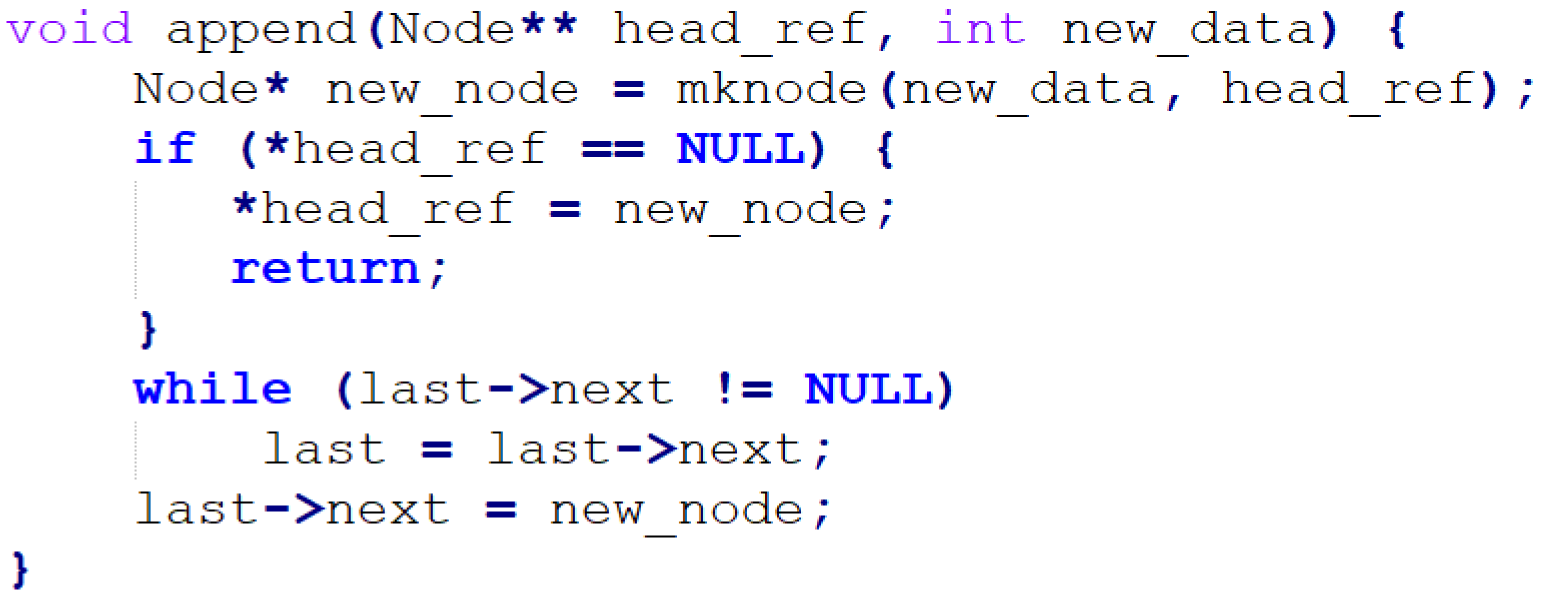

```
void append(Node** head_ref, int new_data) {
    Node* new_node = mknode(new_data, head_ref);
    if (*head_ref == NULL) {
       *head_ref = new_node;
       return;
    }
    while (last->next != NULL)
        last = last->next;
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```
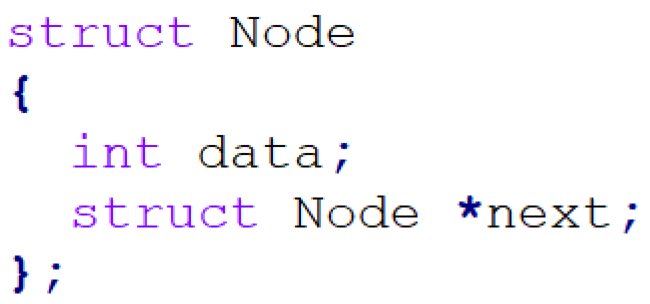

Basic List Append



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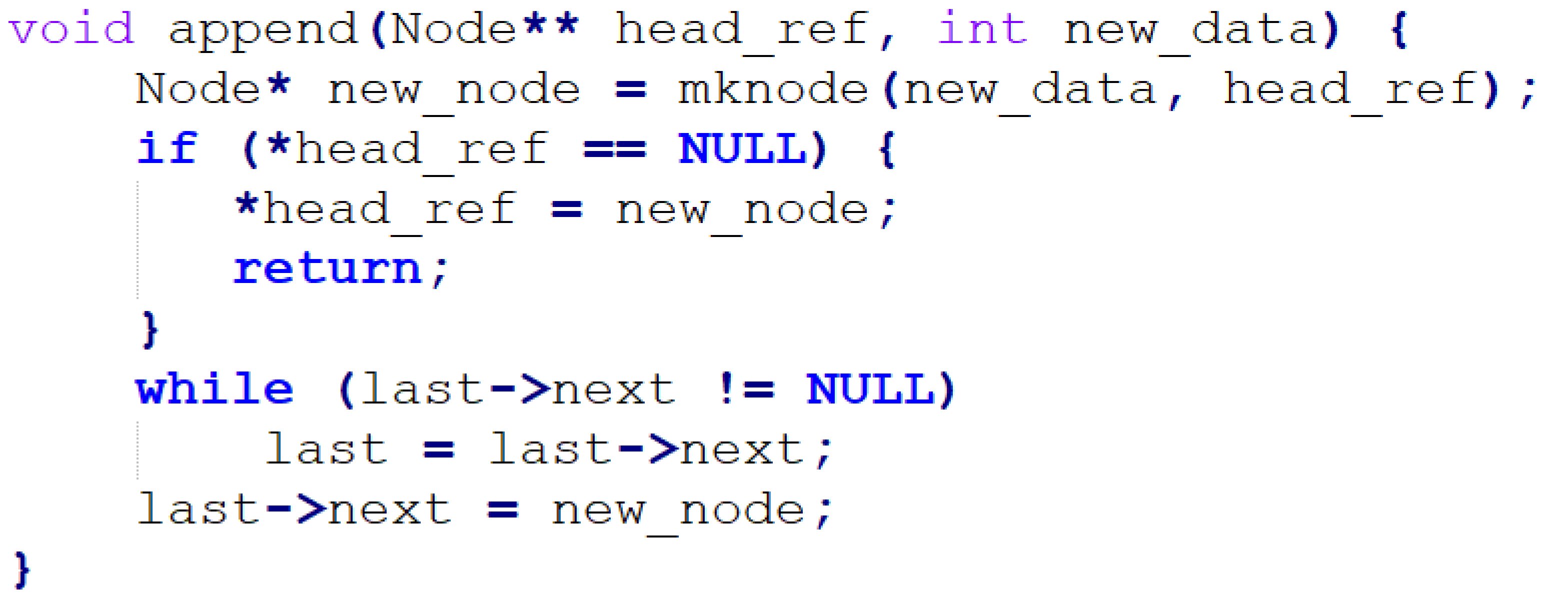

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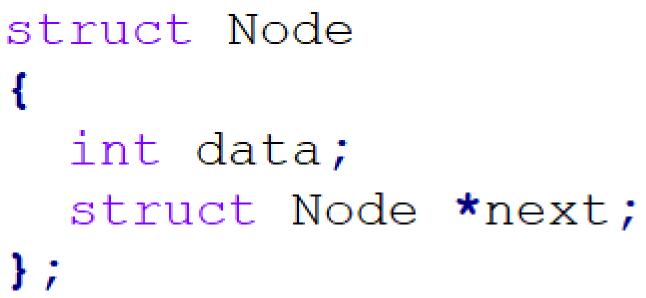
}
```

- Is this thread safe?

Basic List Append



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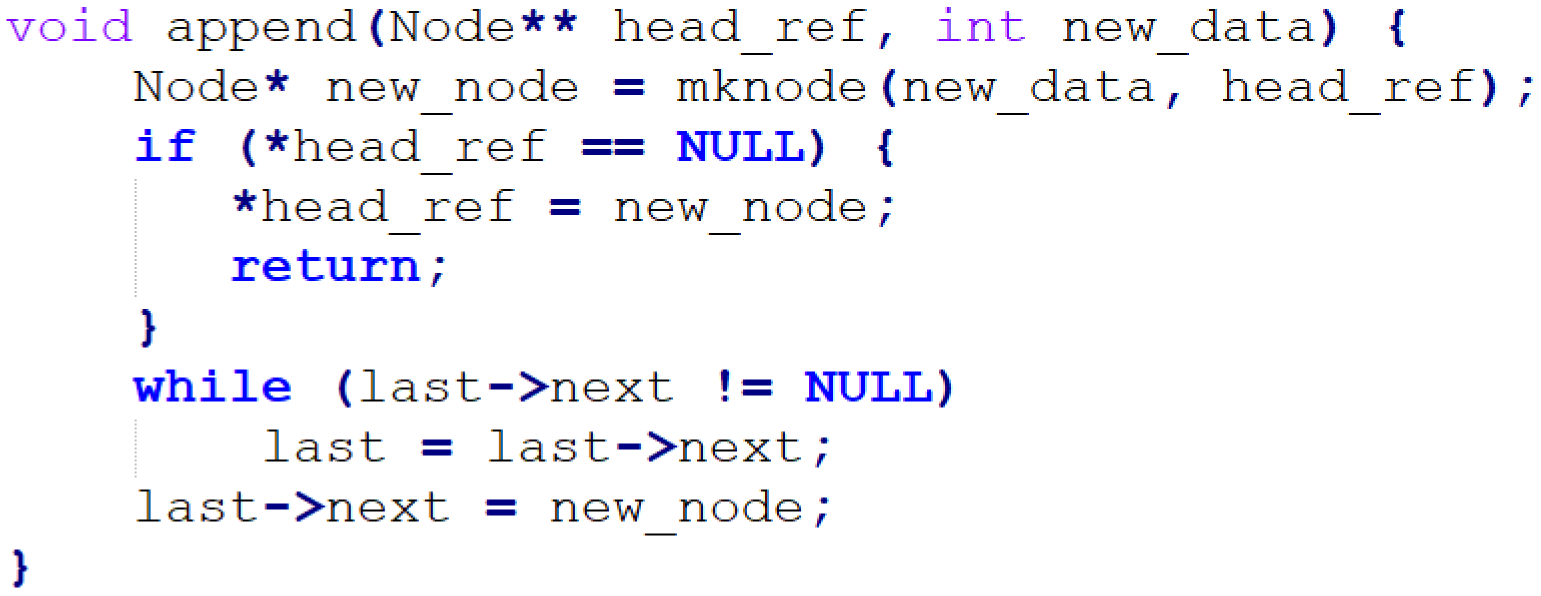

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        return;
    }
    while (last->next != NULL)
         last = last->next;
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}
```

- Is this thread safe?
- What can go wrong?

Example: List Append

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  int data;
  struct Node *next;
};
```

```
void append(Node** head_ref, int new_data) {
    Node* new_node = mknode(new_data, head_ref);
    lock();
    if (*head_ref == NULL) {
        *head_ref = new_node;
    } else {
        while (last->next != NULL)
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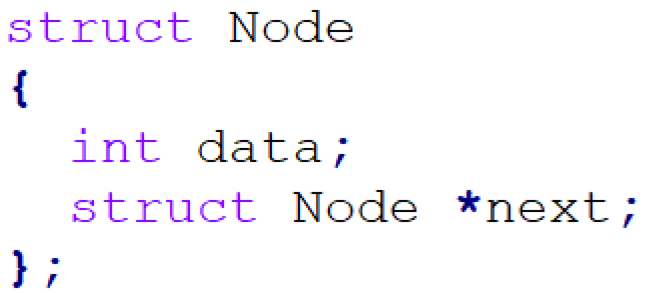
        last->next = new_node;
    }
    unlock();
}
```

Example: List Append



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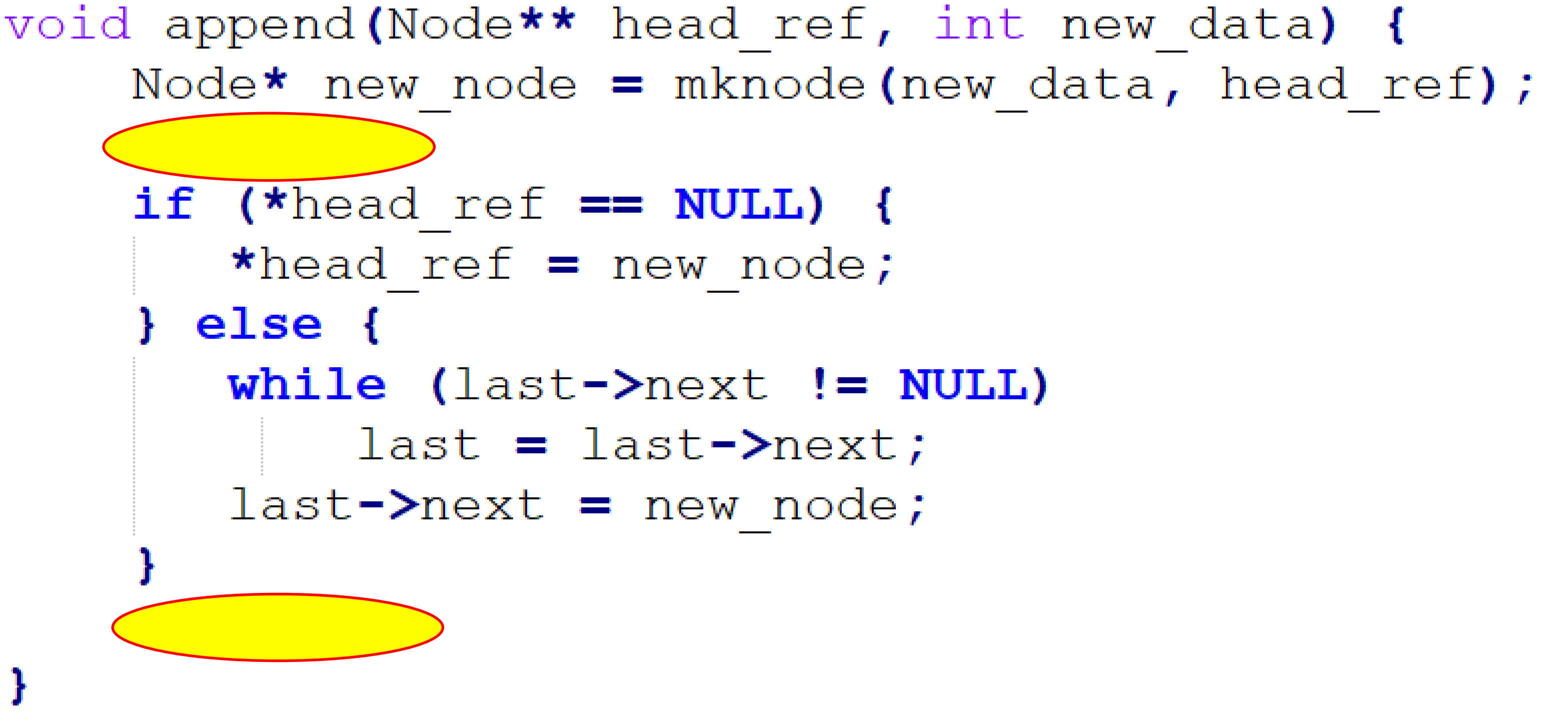

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```

- What property do the locks enforce?

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```

- What property do the locks enforce?
- What does the mutual exclusion ensure?

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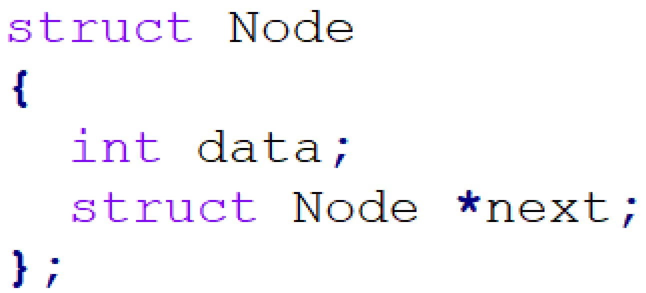

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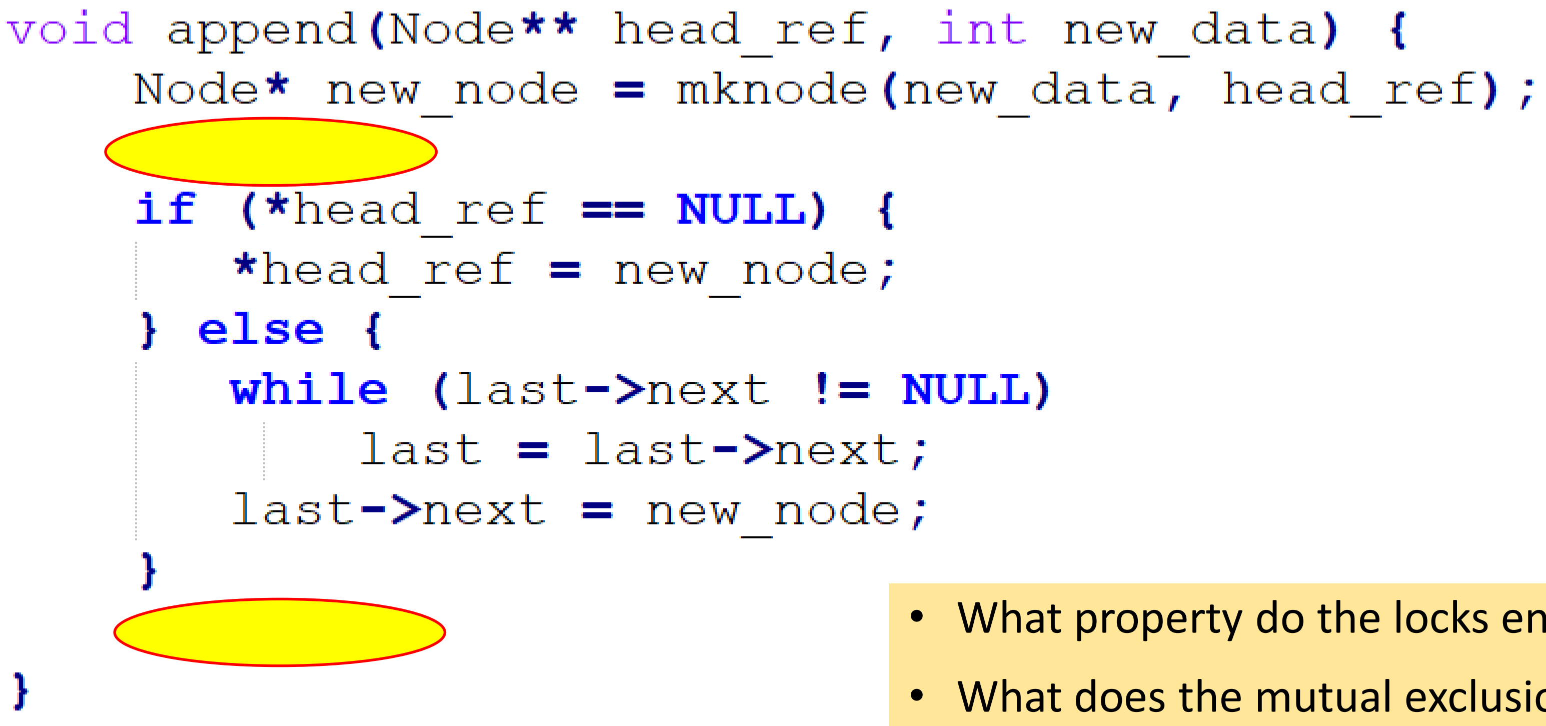

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- What property do the locks enforce?
- What does the mutual exclusion ensure?
- Can we ensure consistent view (invariants hold) sans mutual exclusion?

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}
```

- What property do the locks enforce?
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- Can we ensure consistent view (invariants hold) sans mutual exclusion?
- Key insight: allow inconsistent view and fix it up algorithmically

Example: List Append

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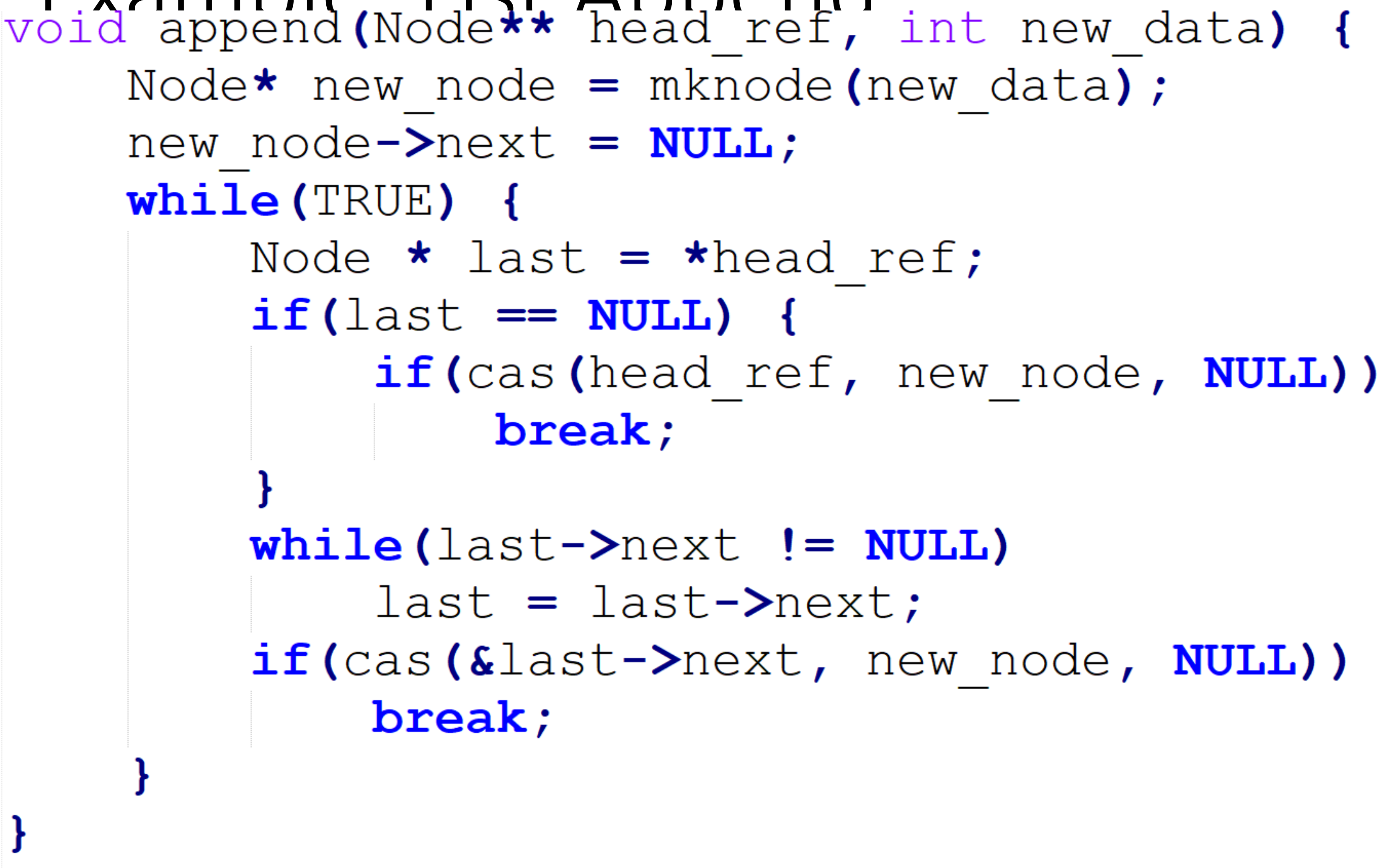
struct Node
       data;
   uct Node *next;
```



```
void append(Node** head_ref, int new_data) {
    Node* new_node = mknode(new_data);
    new_node->next = NULL;
    while(TRUE) {
        Node * last = *head_ref;
        if(last == NULL) {
            if(cas(head_ref, new_node, NULL))
                break;
        }
        while(last->next != NULL)
            last = last->next;
        if(cas(&last->next, new_node, NULL))
            break;
    }
}
```

e?

nsure?

- Can we ensure consistent view (invariants hold) sans mutual exclusion?
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Example: SP-SC Queue

```
next(x):
    if(x == Q_size-1) return 0;
    else return x+1;
```

```
Q_get(data):
    t = Q_tail;
    while(t == Q_head)
      ;
    data = Q_buf[t];
    Q_tail = next(t);
```

```
Q_put(data):
    h = Q_head;
    while(next(h) == Q_tail)
      ;
    Q_buf[h] = data;
    Q_head = next(h);
```

- Single-producer single-consumer
- Why/when does this work?

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Q_put(data):
    h = Q_head;
    while(next(h) == Q_tail)
      ;
    Q_buf[h] = data;
    Q_head = next(h);
```
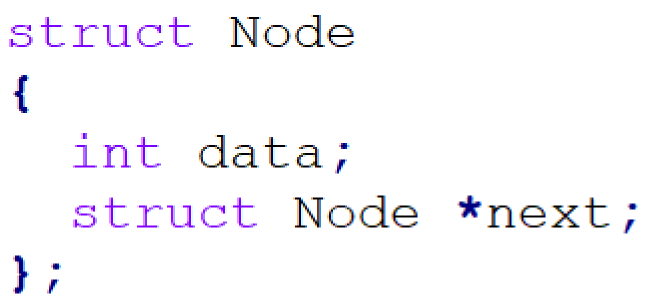

1. Q_head is last write in Q_put, so Q_get never gets "ahead".
2. *single* p,c only (as advertised)
3. Requires fence before setting Q head
4. Devil in the details of "wait"
5. No lock → "optimistic"

- Single-producer single-consumer
- Why/when does this work?

Lock-Free Stack



```
struct Node
{
  int data;
  struct Node *next;
};
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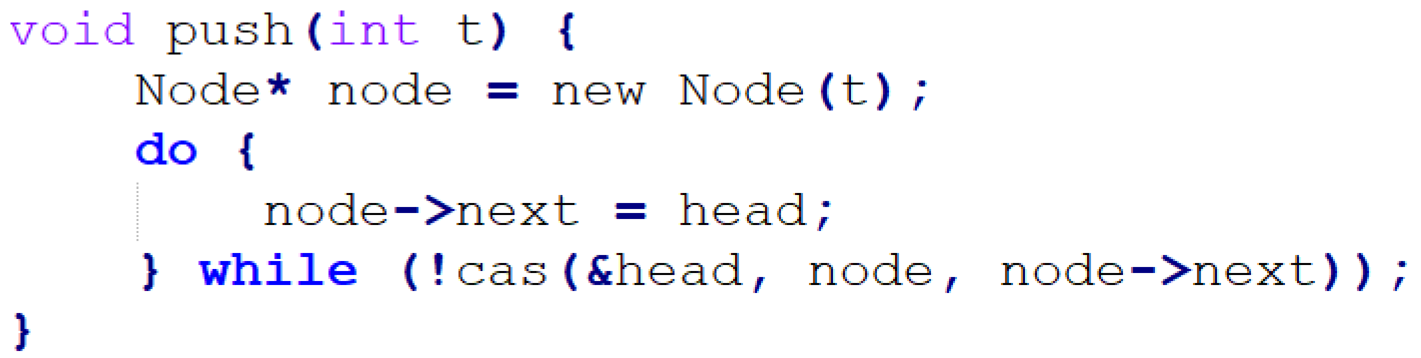
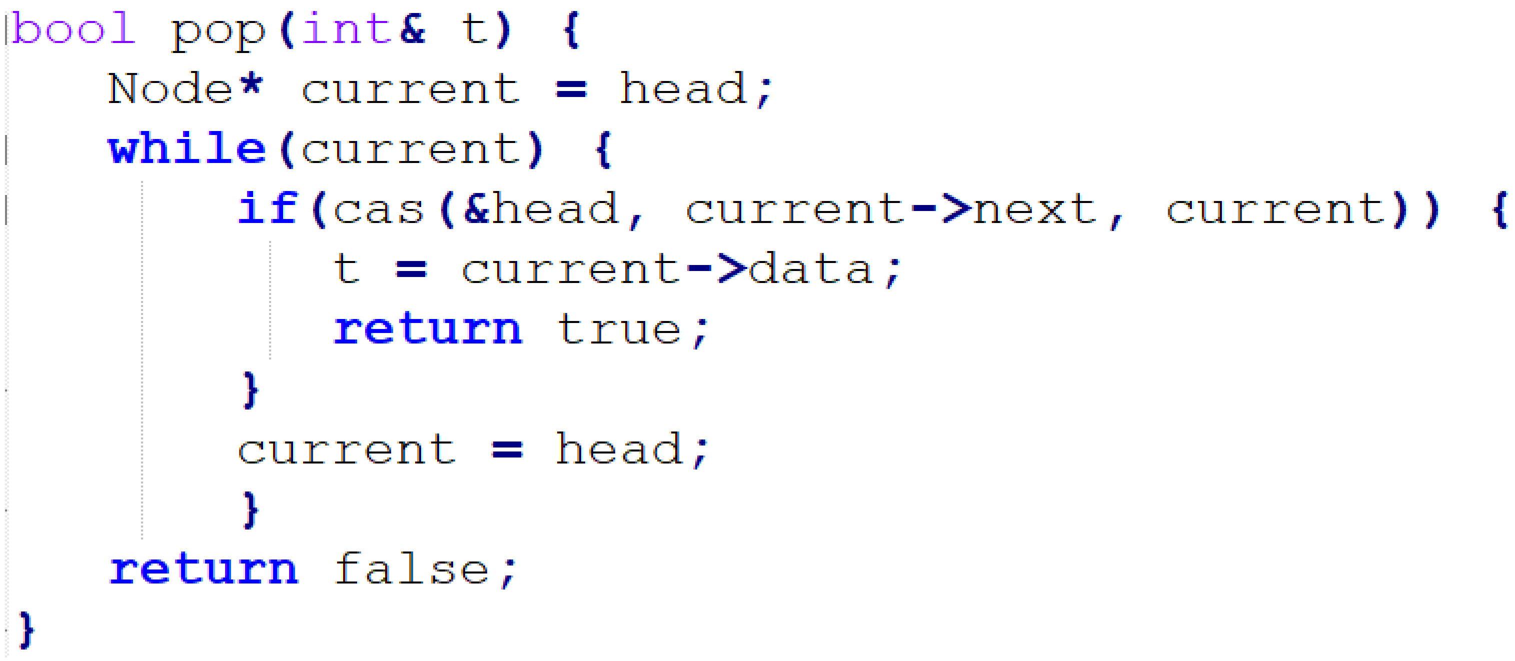
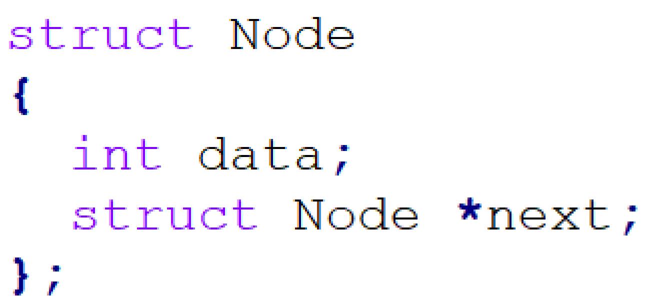


```
void push(int t) {
    Node* node = new Node(t);
    do {
        node->next = head;
    } while (!cas(&head, node, node->next));
}
```



```
bool pop(int& t) {
   Node* current = head;
   while(current) {
       if(cas(&head, current->next, current)) {
          t = current->data;
          return true;
       }
       current = head;
       }
   return false;
}
```

Lock-Free Stack



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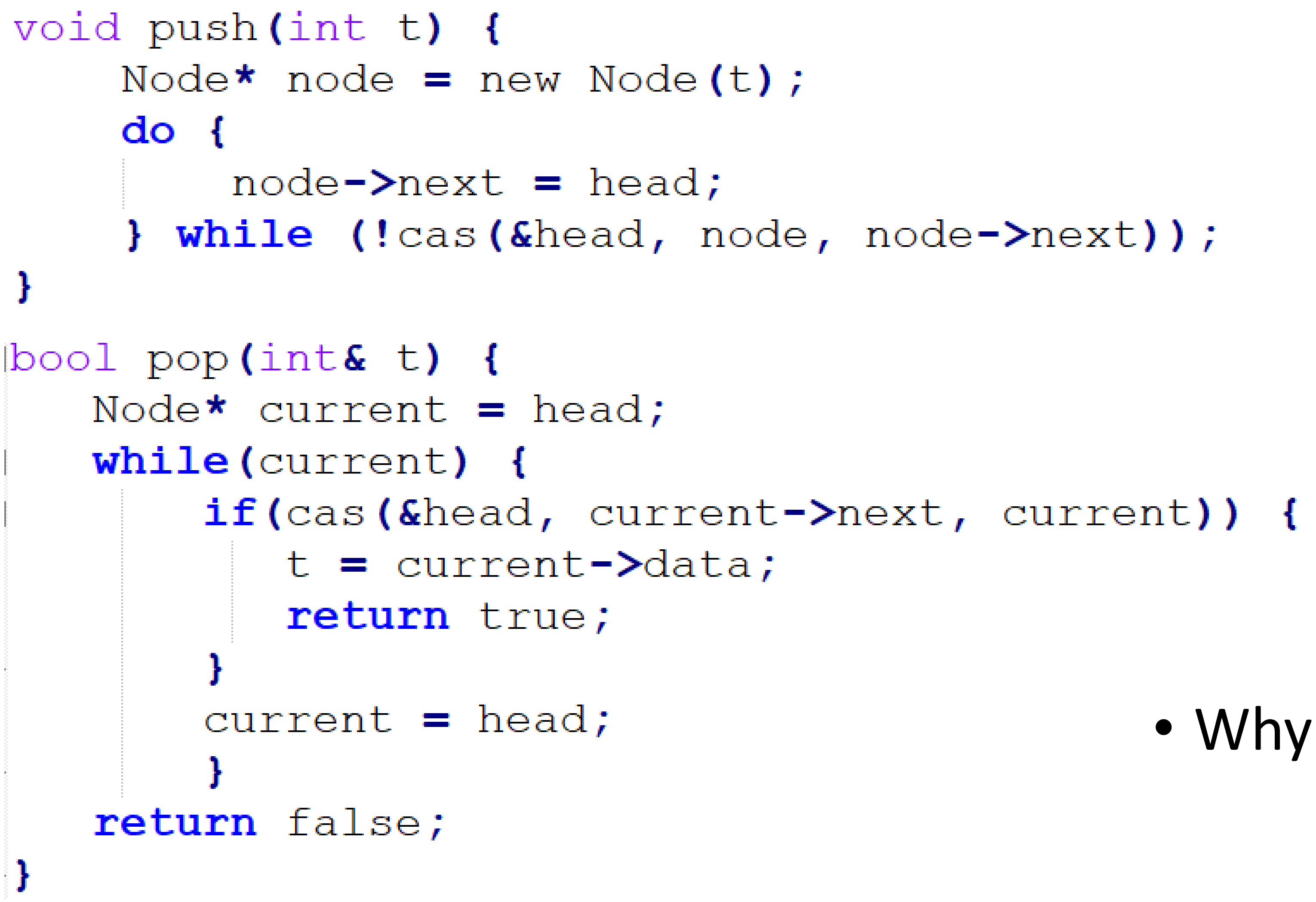

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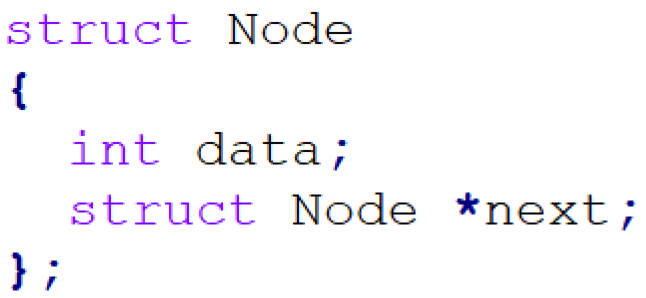
- Why does is it work?

Lock-Free Stack



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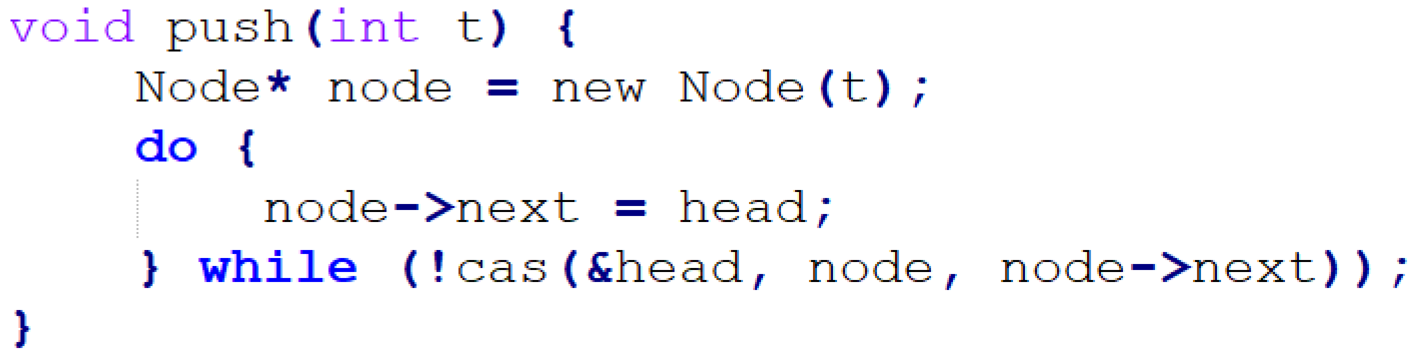

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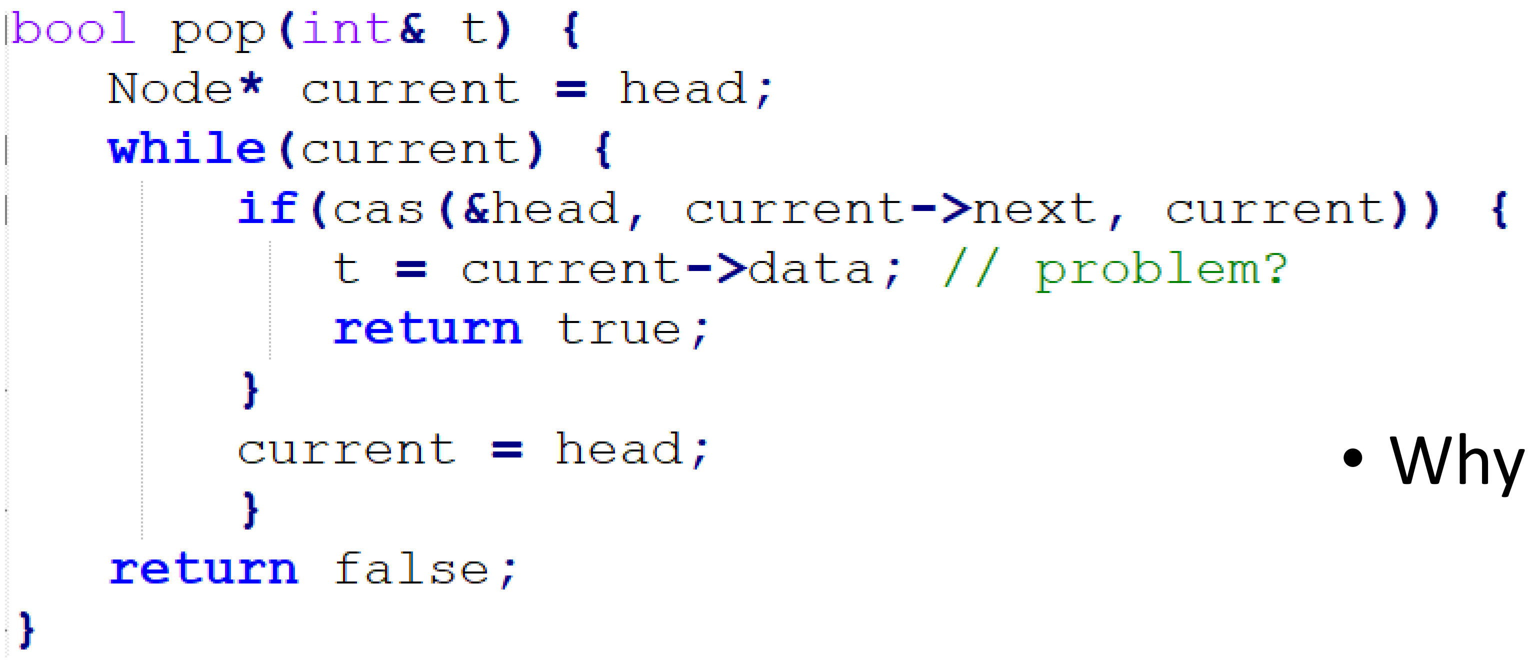

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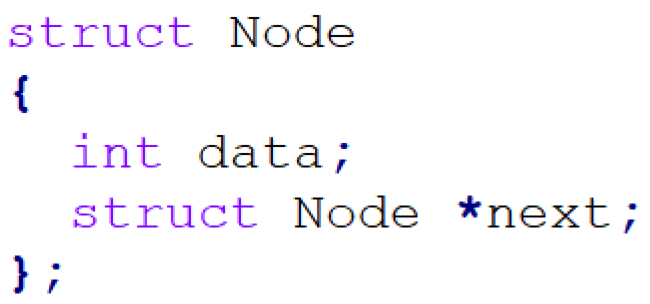
Lock-Free Stack



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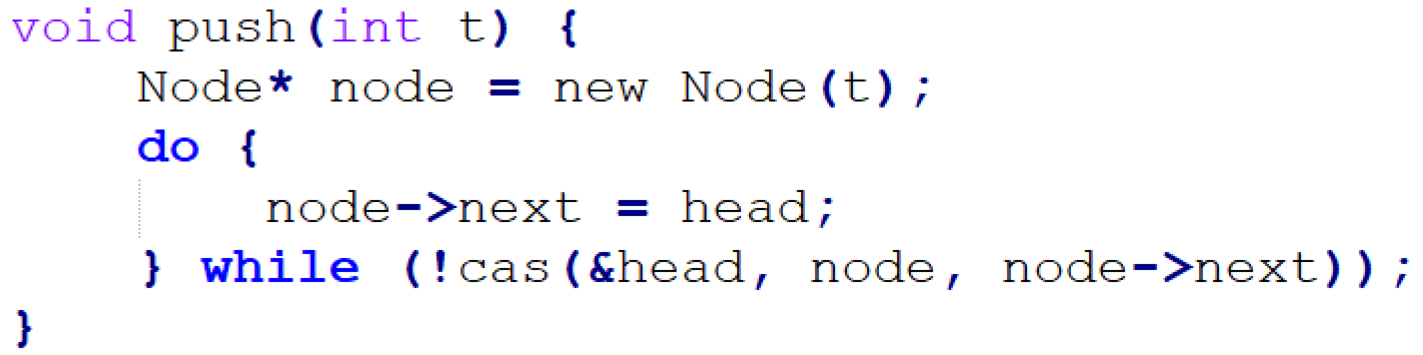

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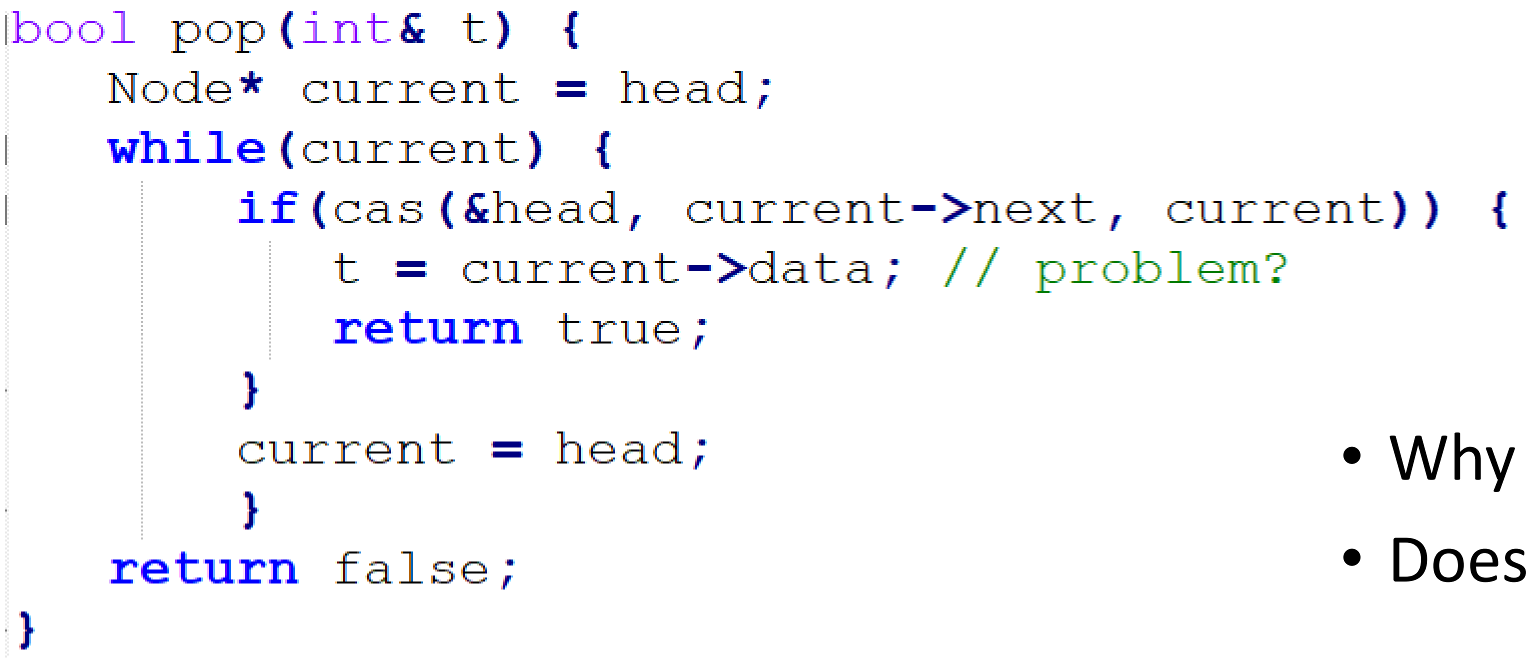

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```
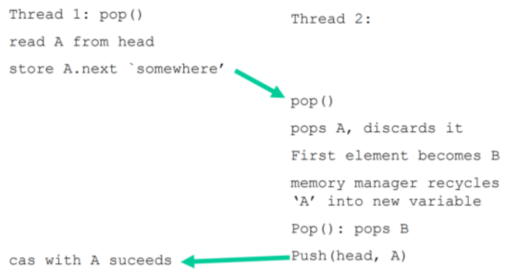

- Why does is it work?
- Does it enforce all invariants?

Lock-Free Stack: ABA Problem



Thread 1: pop()

read A from head

store A.next `somewhere'

cas with A suceeds

Thread 2:

pop()

pops A, discards it

First element becomes B

memory manager recycles
'A' into new variable

Pop(): pops B

Push(head, A)

Lock-Free Stack: ABA Problem

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    }
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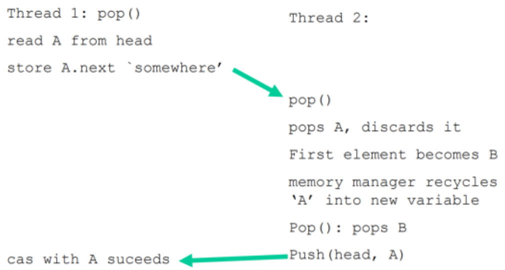
}
```



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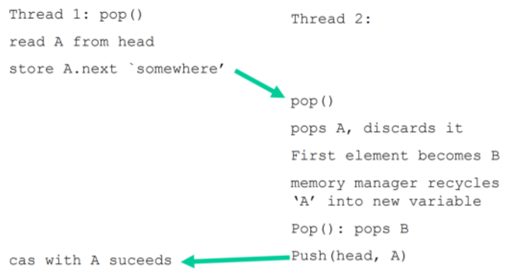

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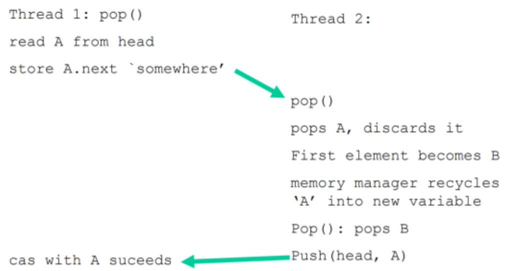

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        current = head;
    }
    return false;
}
```
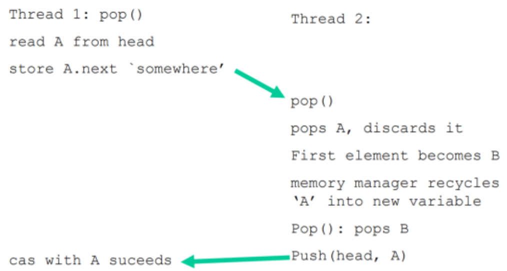

```
Node* pop() {
    Node* current = head;
    while(current) {
```

```
Node * node = pop();
delete node;
node = new Node(blah_blah);
push(node);
```



Thread 1: pop()

read A from head

store A.next `somewhere’

Thread 2:

pop()

pops A, discards it

First element becomes B

memory manager recycles
‘A’ into new variable

Pop(): pops B

Push(head, A)

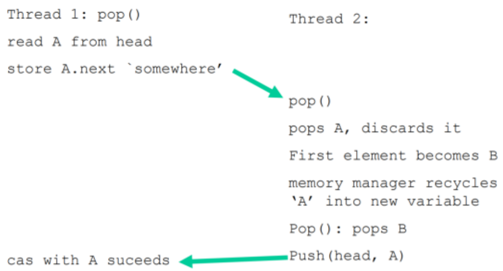
cas with A suceeds

Lock-Free Stack: ABA Problem

```
Node* pop() {
    Node* current = head;
    while(current) {
        if(cas(&head, current->next, current))
            return current;
        current = head;
    }
    return false;
}
```

```
Node* pop() {
    Node* current = head;
    while(current) {





        if(cas(&head, current->next, current))
            return current;
        current = head;
    }
    return false;
}
```

```
Node * node = pop();
delete node;
node = new Node(blah_blah);
push(node);
```



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Thread 1: pop()	Thread 2:
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	memory manager recycles ‘A’ into new variable
	Pop(): pops B
cas with A suceeds	Push(head, A)

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            return current;
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read A from head

store A.next `somewhere’

Thread 2:

pop()

pops A, discards it

First element becomes B

memory manager recycles ‘A’ into new variable

Pop(): pops B

Push(head, A)

cas with A suceeds

ABA Problem

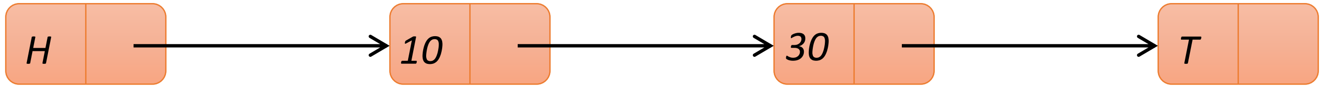
- Thread 1 observes shared variable → ‘A’
- Thread 1 calculates using that value
- Thread 2 changes variable to B
  - if Thread 1 wakes up now and tries to CAS, CAS fails and Thread 1 retries
- Instead, Thread 2 changes variable back to A!
  - Very bad if the variables are pointers

- Anyone see a work-around?

- Keep update count → DCAS
- Avoid re-using memory
- Multi-CAS support → HTM

Correctness: Searching a sorted list

- find(20):



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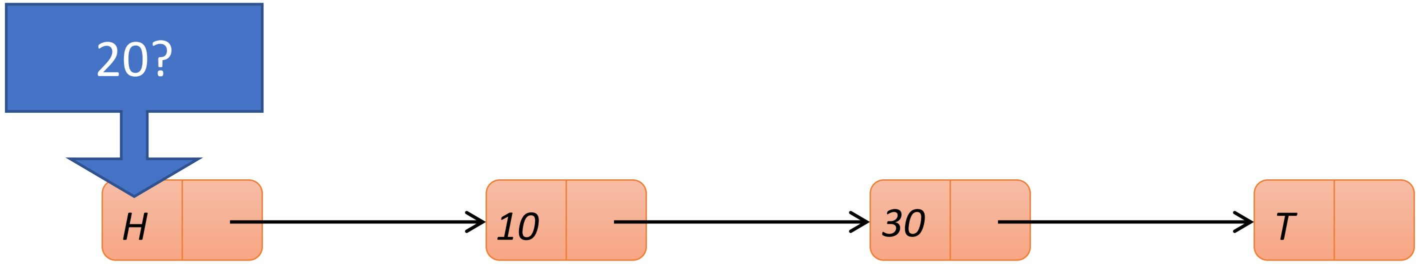

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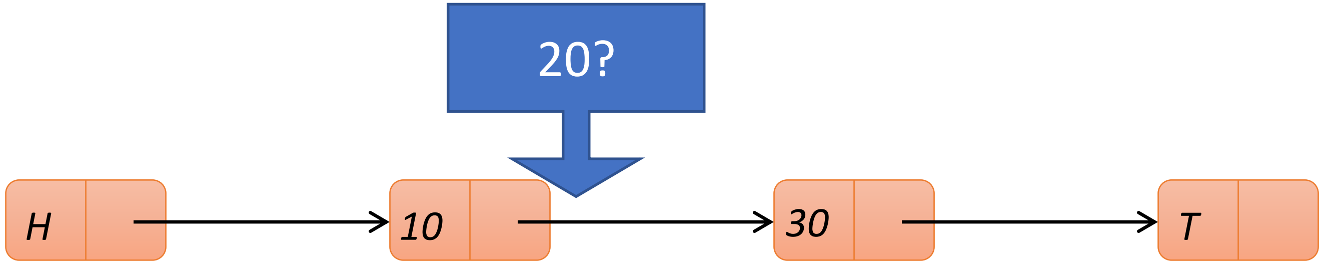

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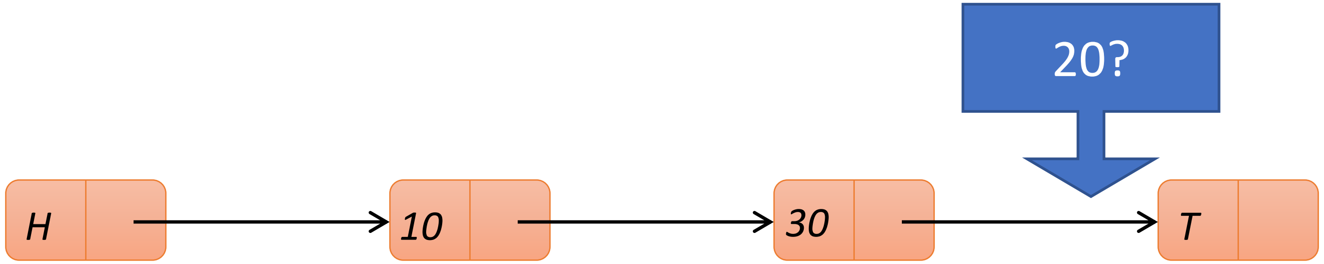
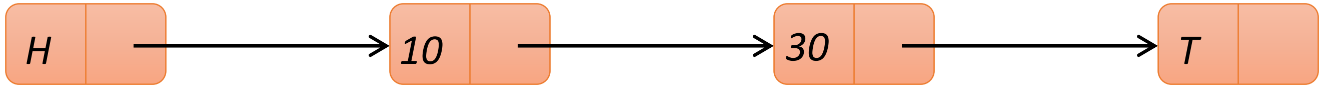


find(20) -> false

Inserting an item with CAS

- insert(20):



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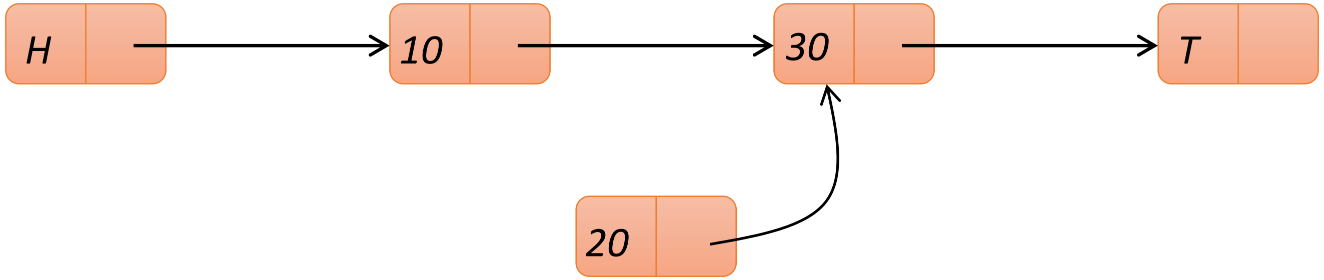

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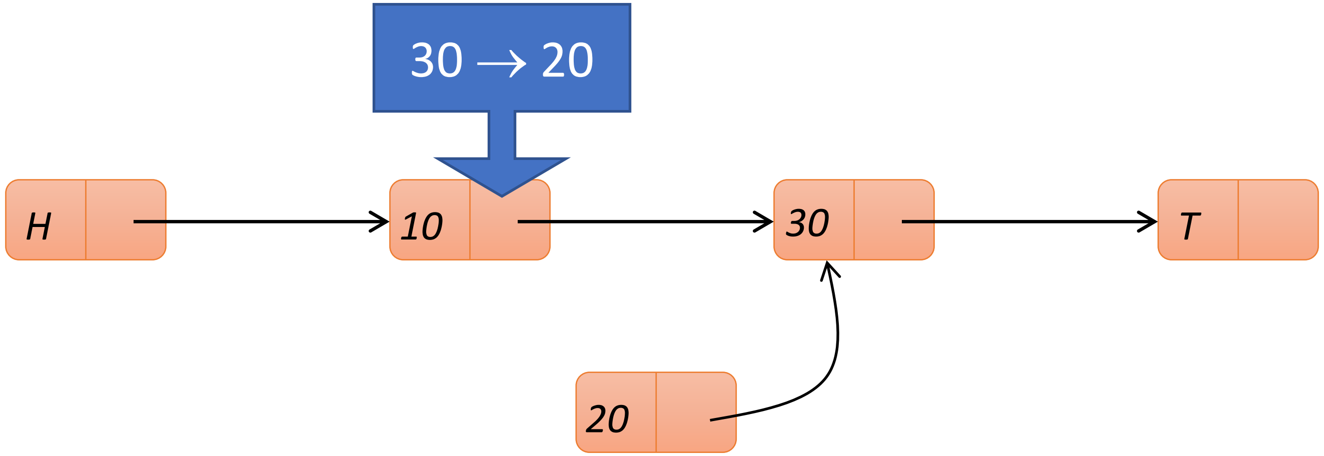

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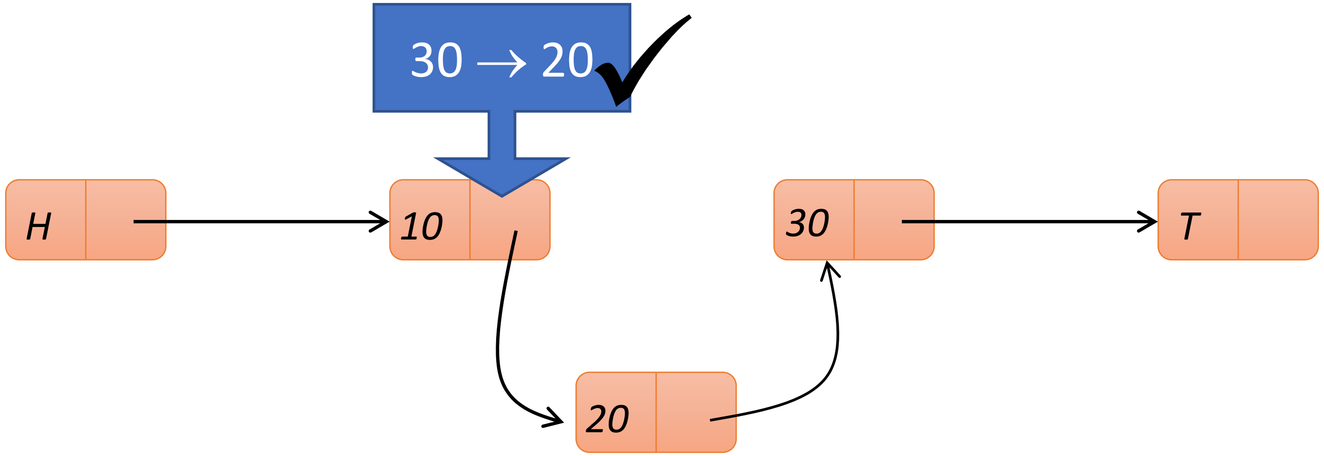

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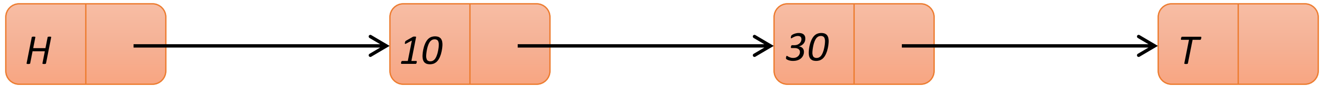

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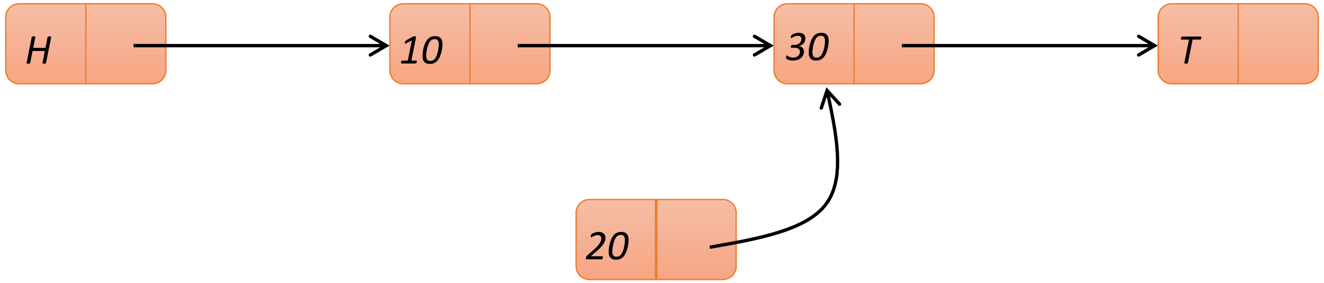

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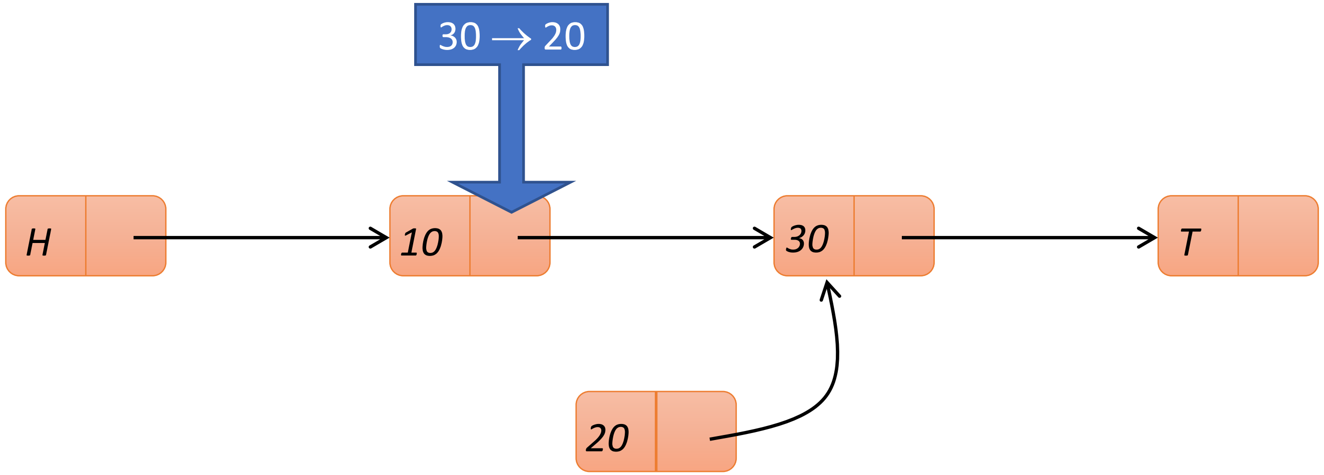

Inserting an item with CAS

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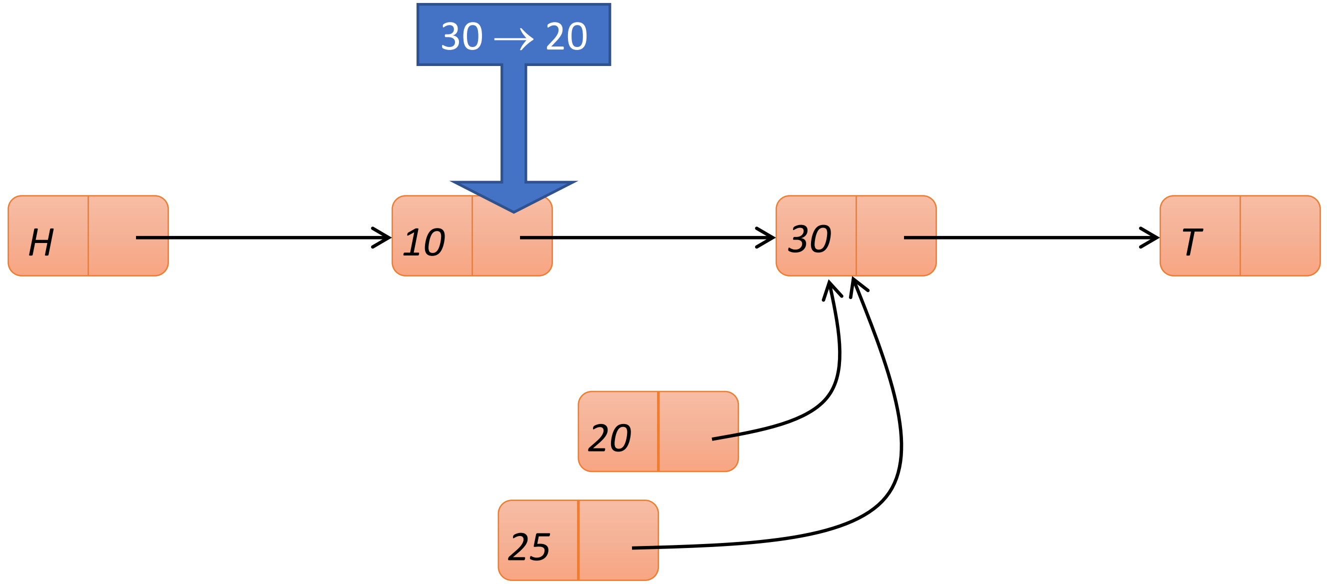
- insert(25):



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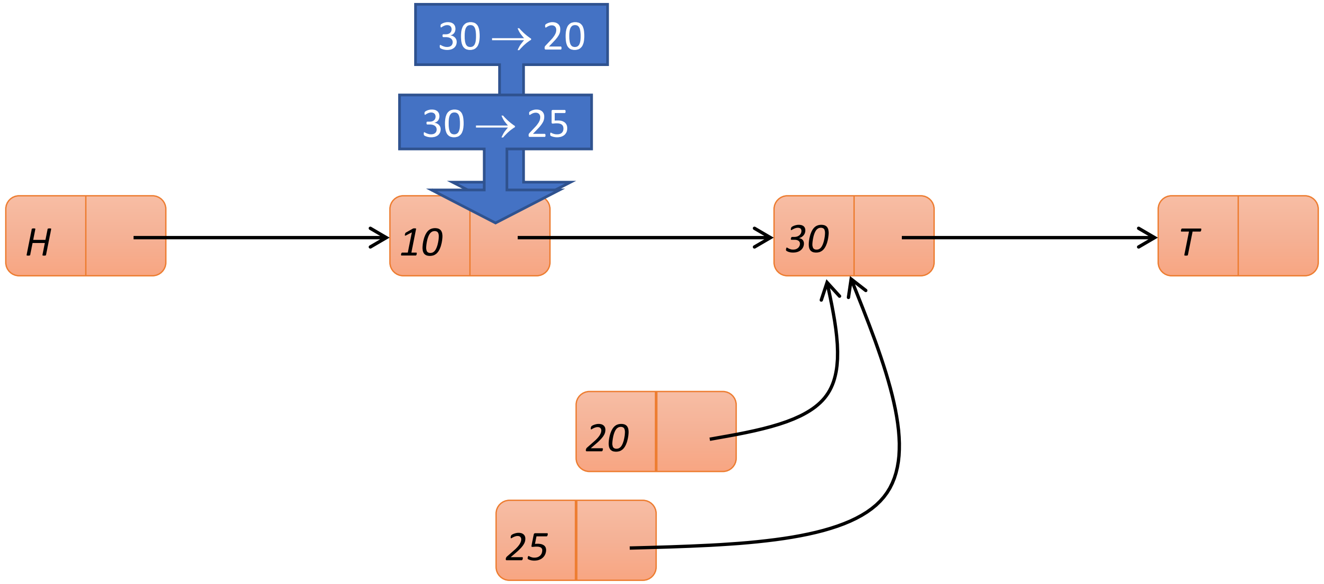

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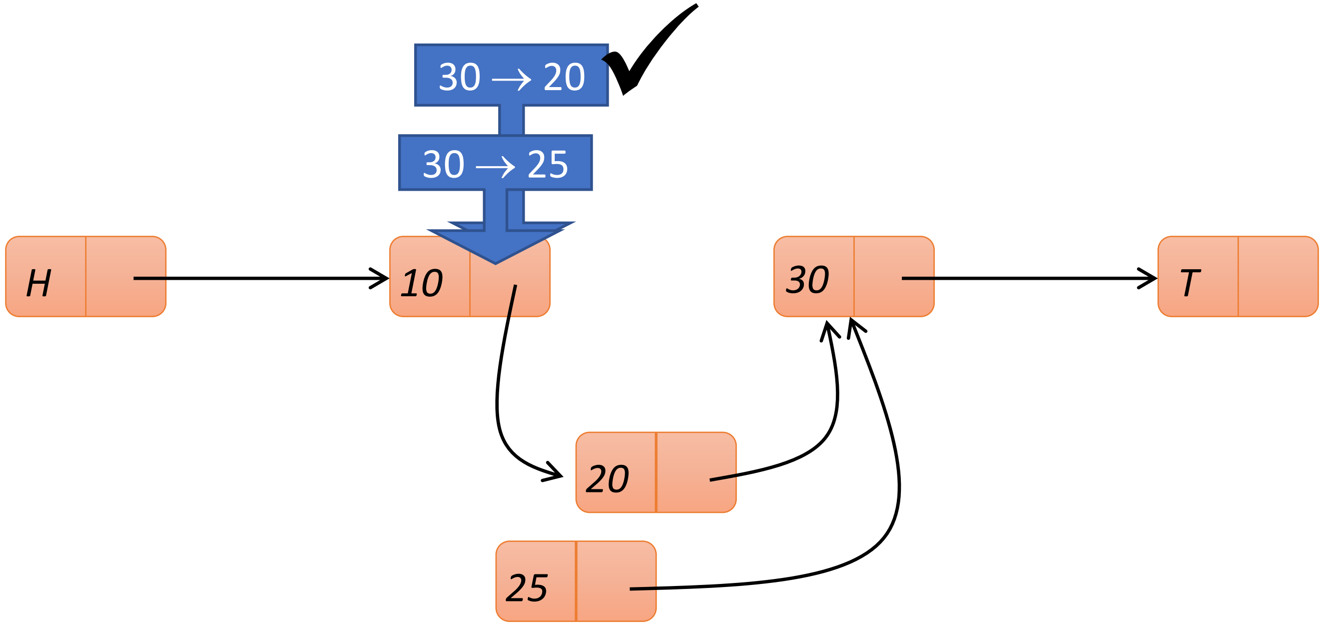

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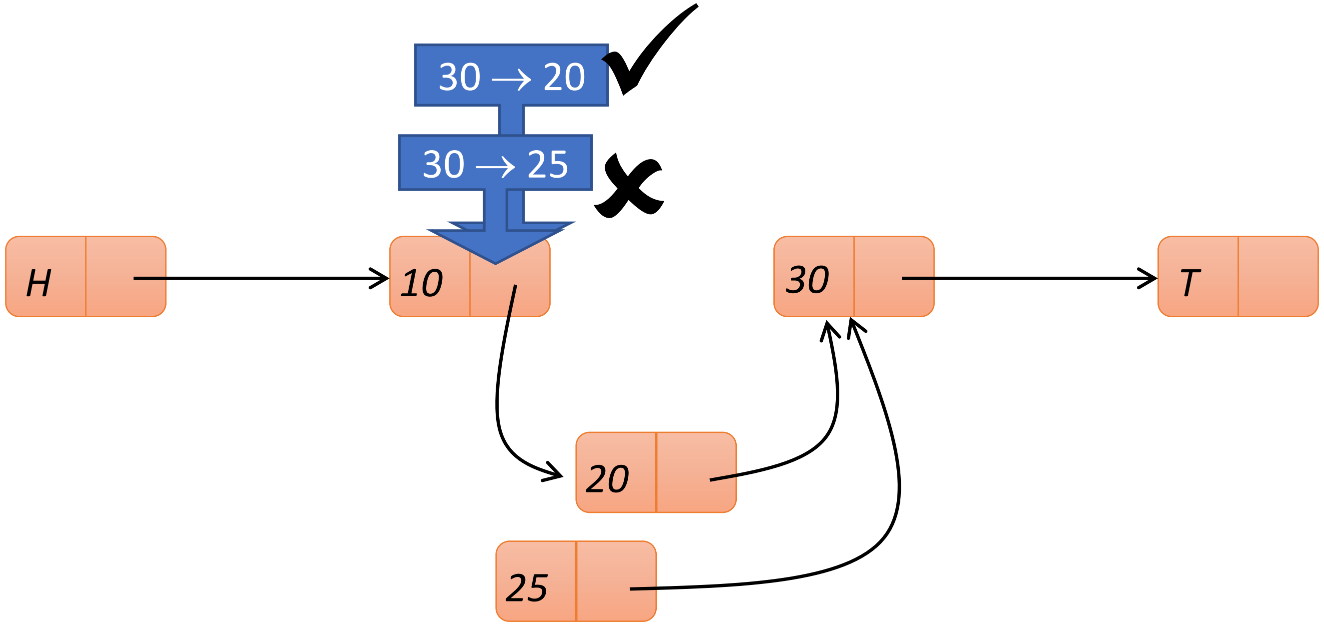

Searching and finding together

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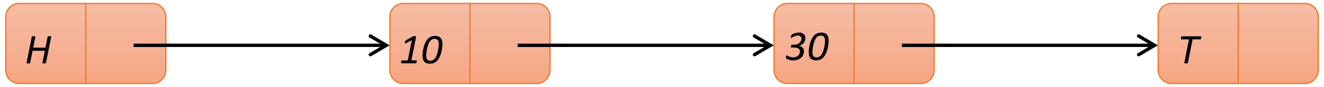

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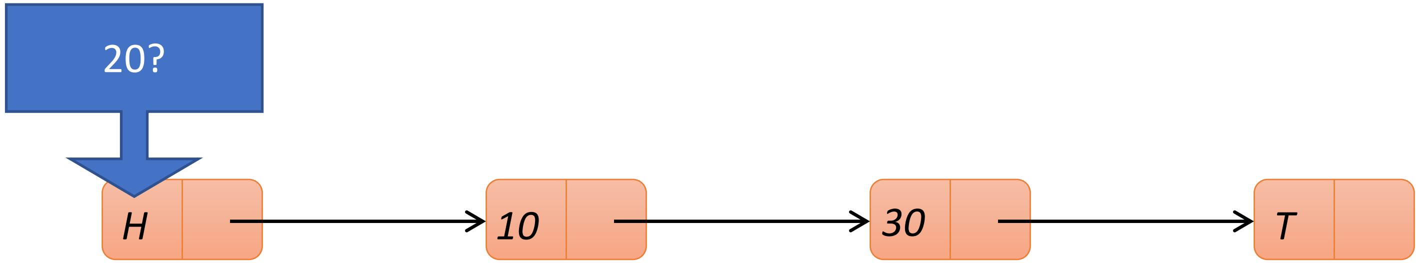

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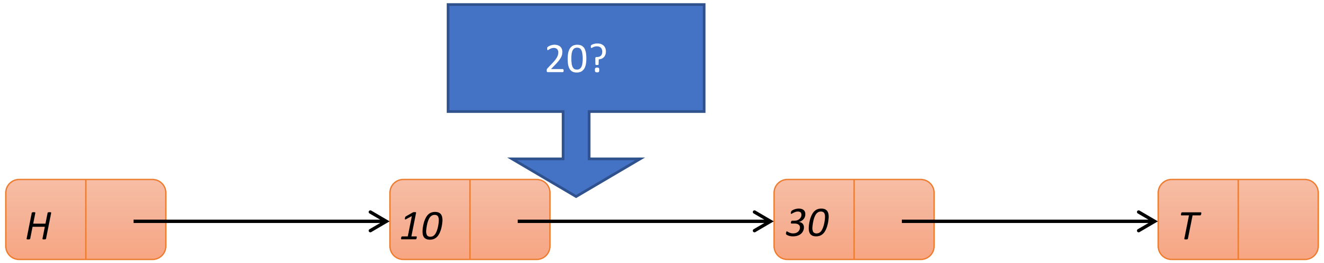

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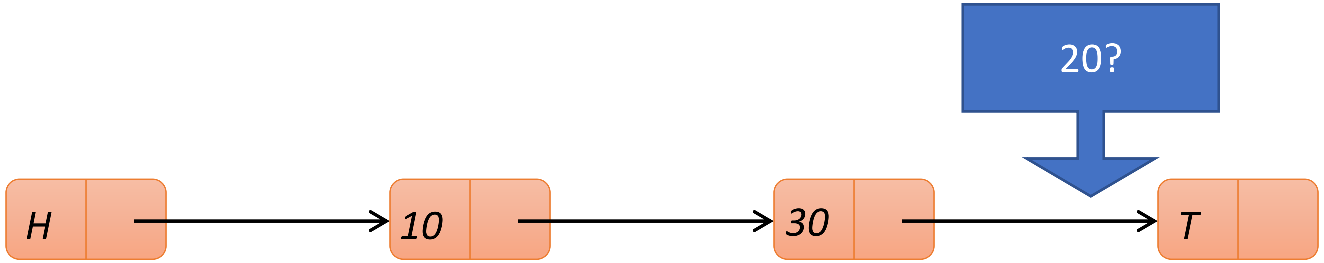

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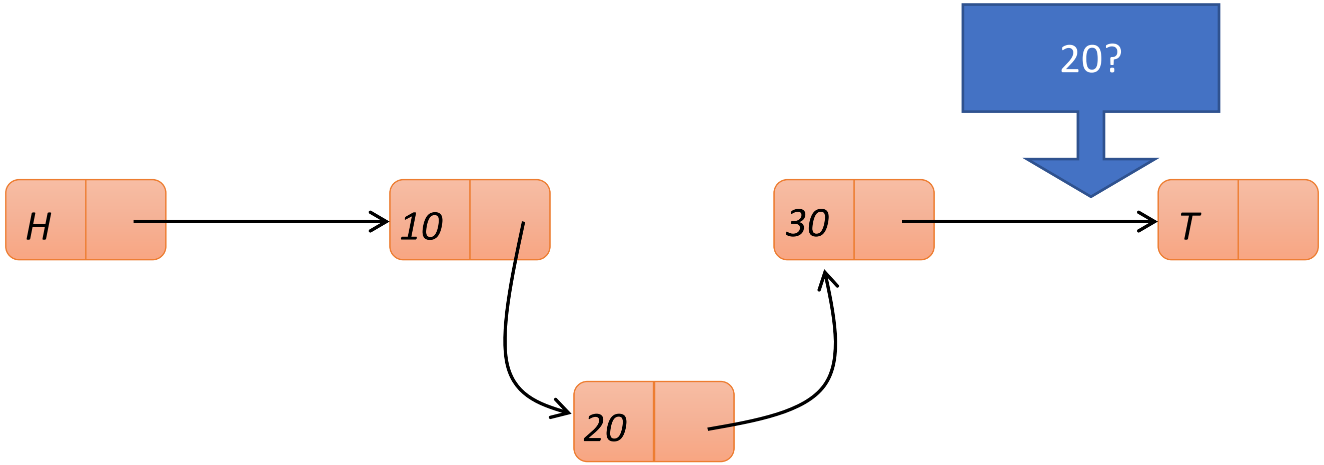

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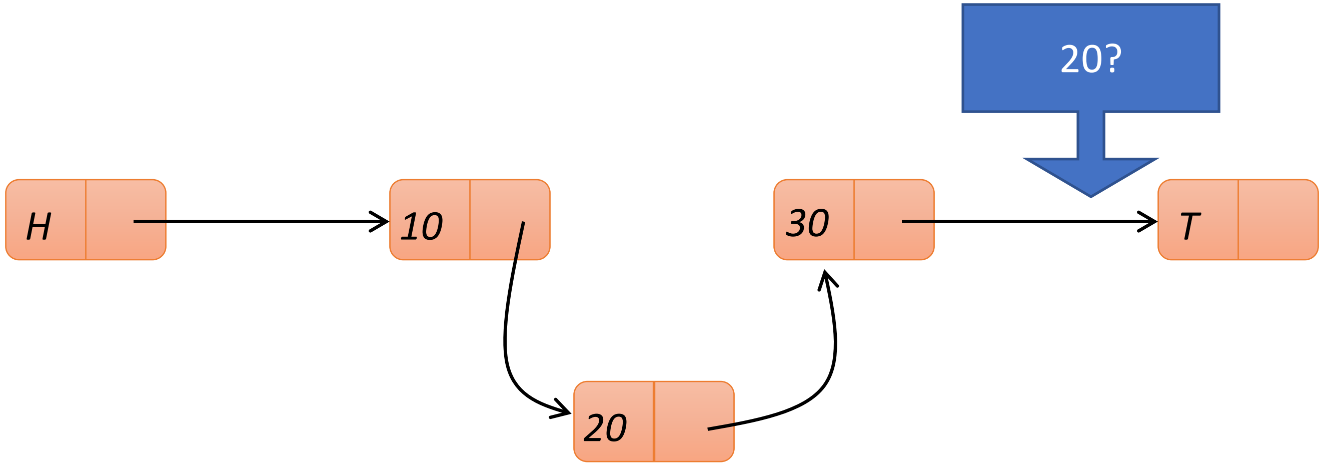

Searching and finding together

- find(20) -> false

This thread saw 20 was not in the set...

- insert(20) -> true

...but this thread succeeded in putting it in!

- Is this a correct implementation?
- Should the programmer be surprised if this happens?
- What about more complicated mixes of operations?

Correctness criteria

Informally:

Look at the behaviour of the data structure

- what operations are called on it
- what their results are

If behaviour is indistinguishable from atomic calls to a sequential implementation then the concurrent implementation is correct.

Sequential history

- No overlapping invocations

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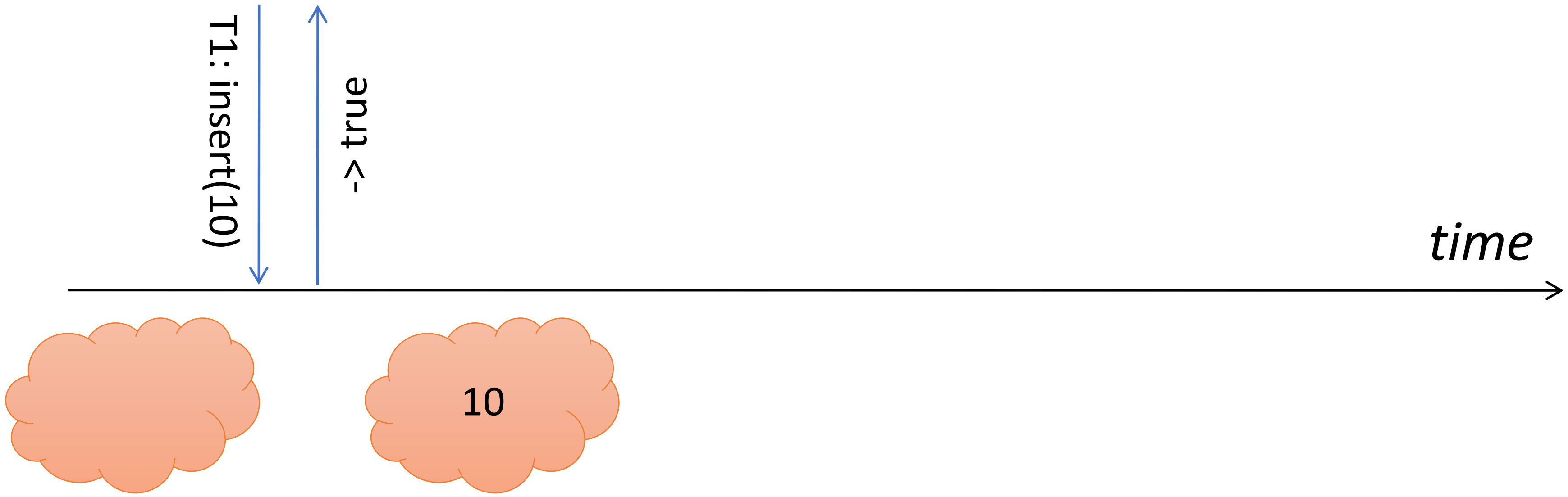

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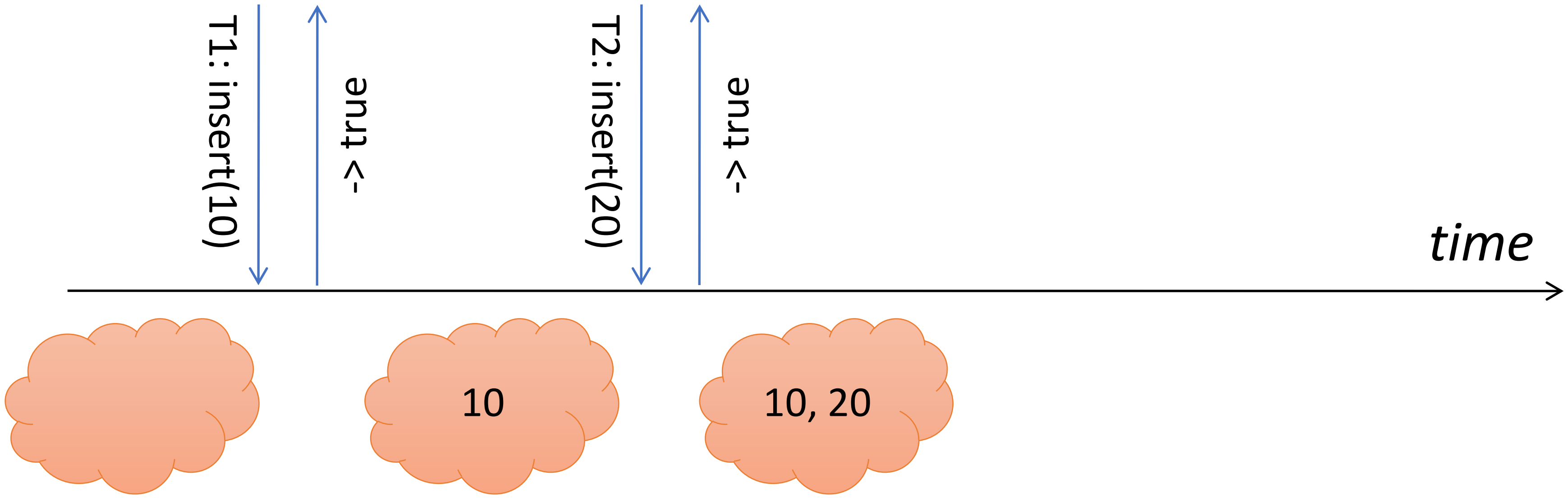

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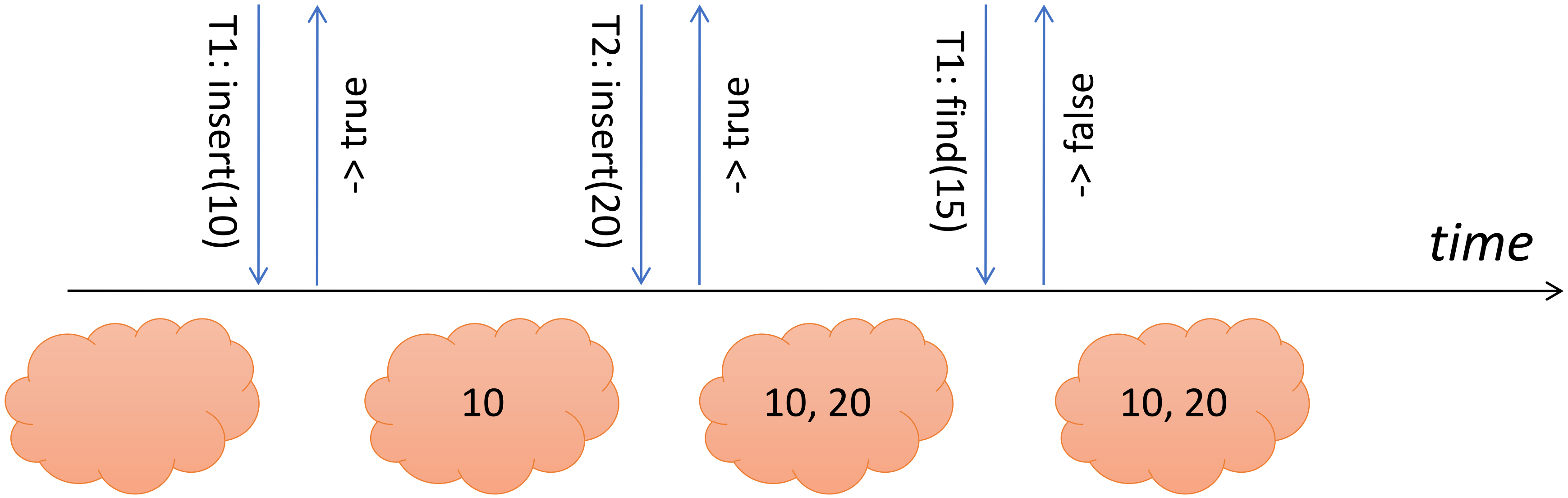

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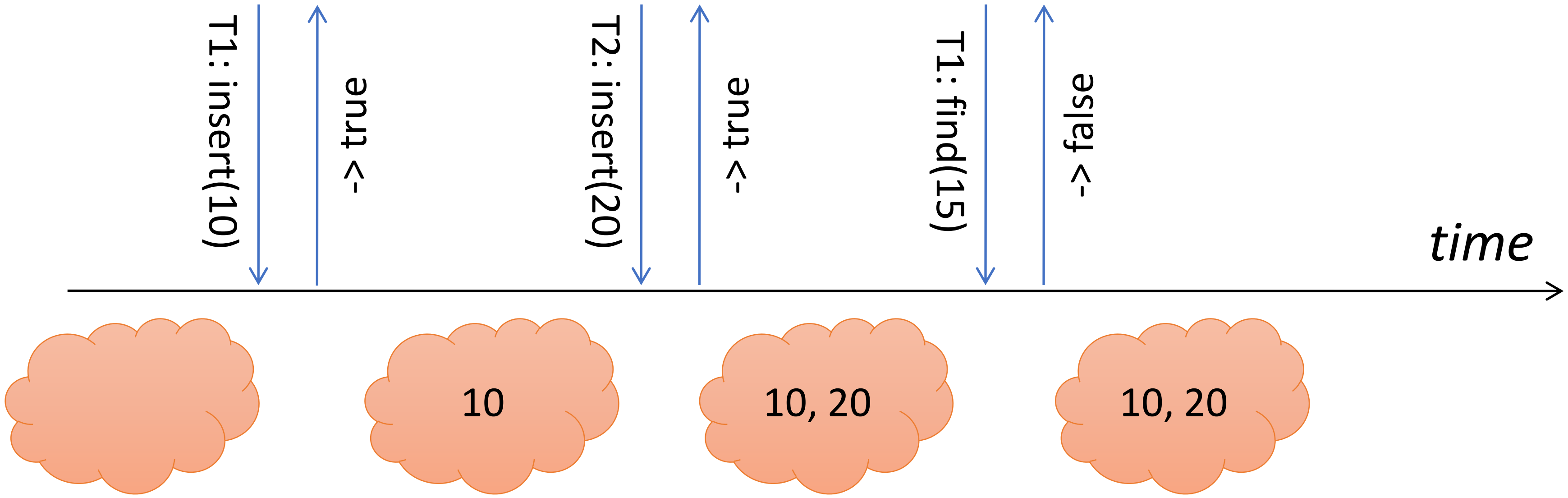
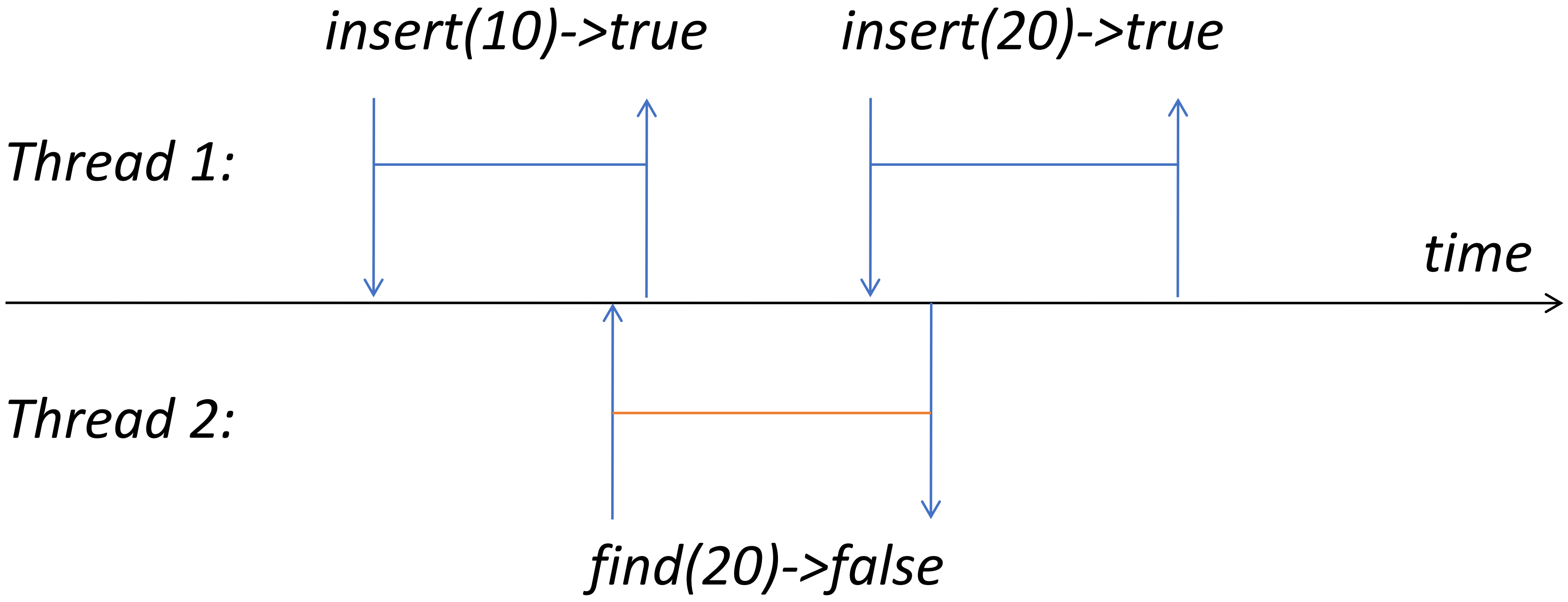


Linearizability: concurrent behaviour should be similar

- even when threads can see intermediate state
- Recall: mutual exclusion precludes overlap

Concurrent history

Allow *overlapping* invocations



Concurrent history

Linearizability:

- Is there a correct sequential history:
  - Same results as the concurrent one
  - Consistent with the timing of the invocations/responses?
  - Start/end impose ordering constraints

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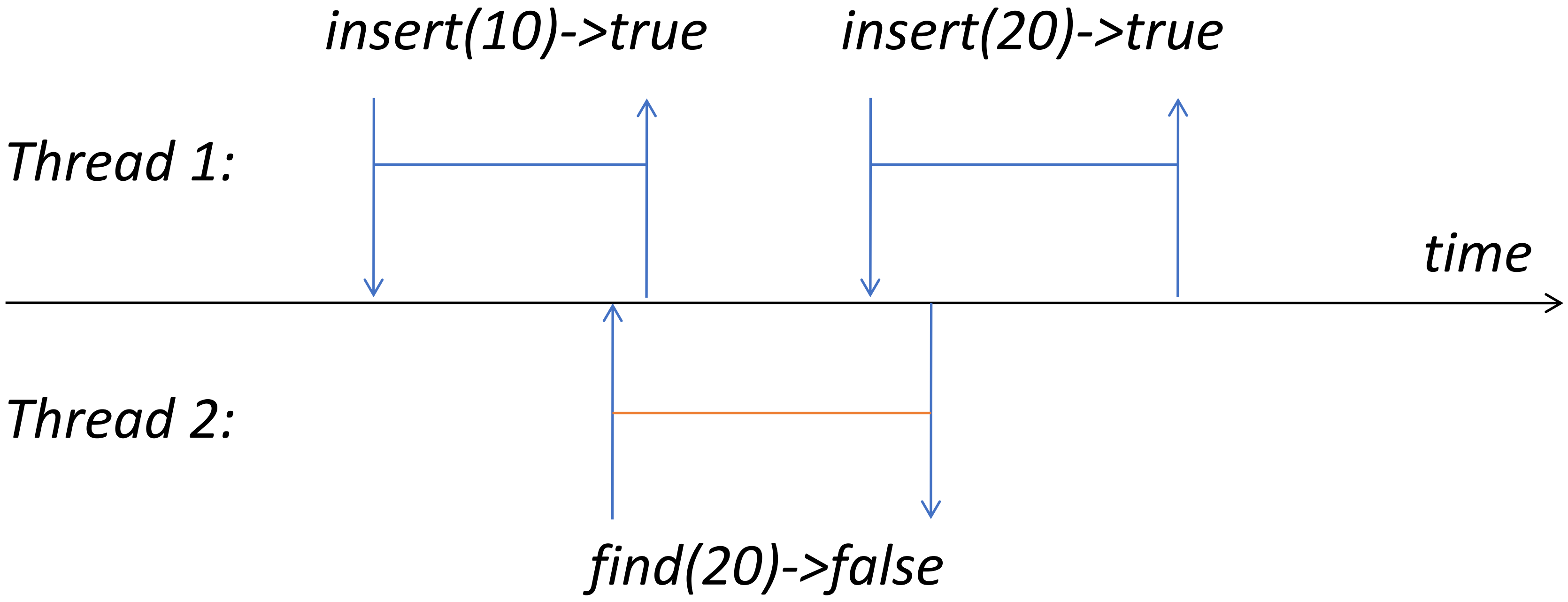

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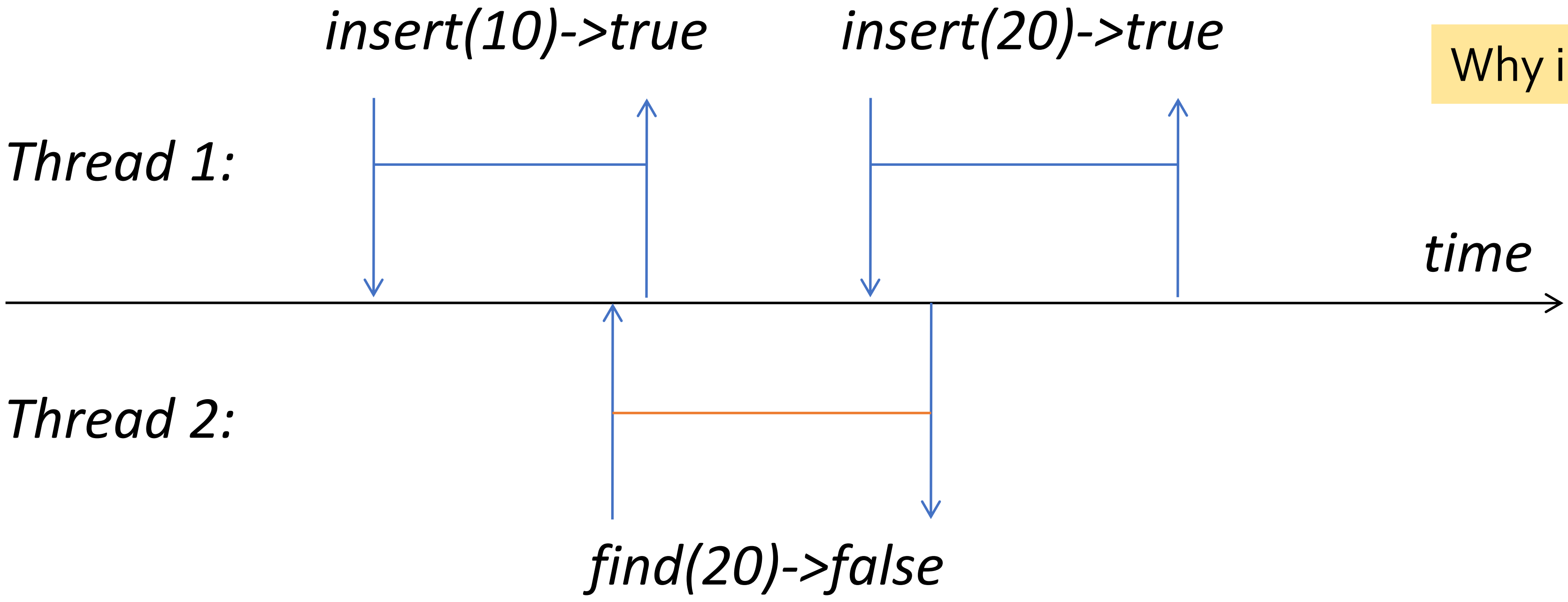

Why is this one OK?

Concurrent history

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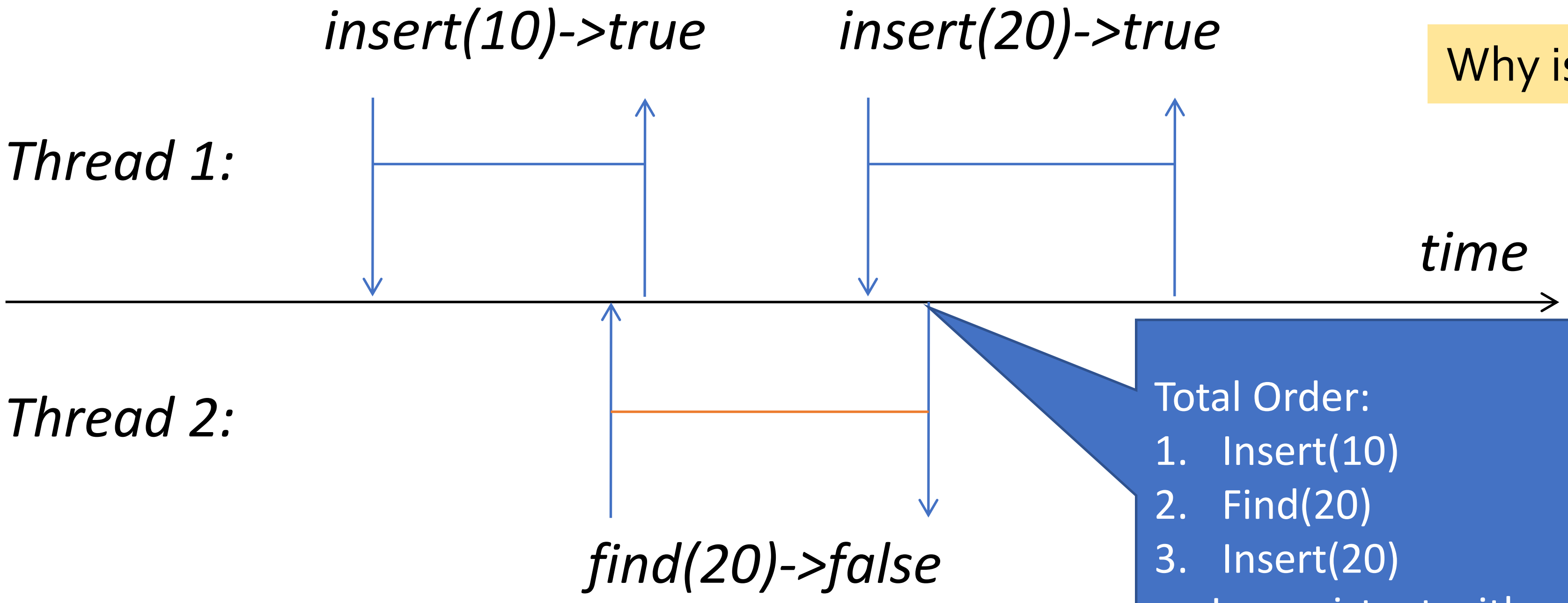


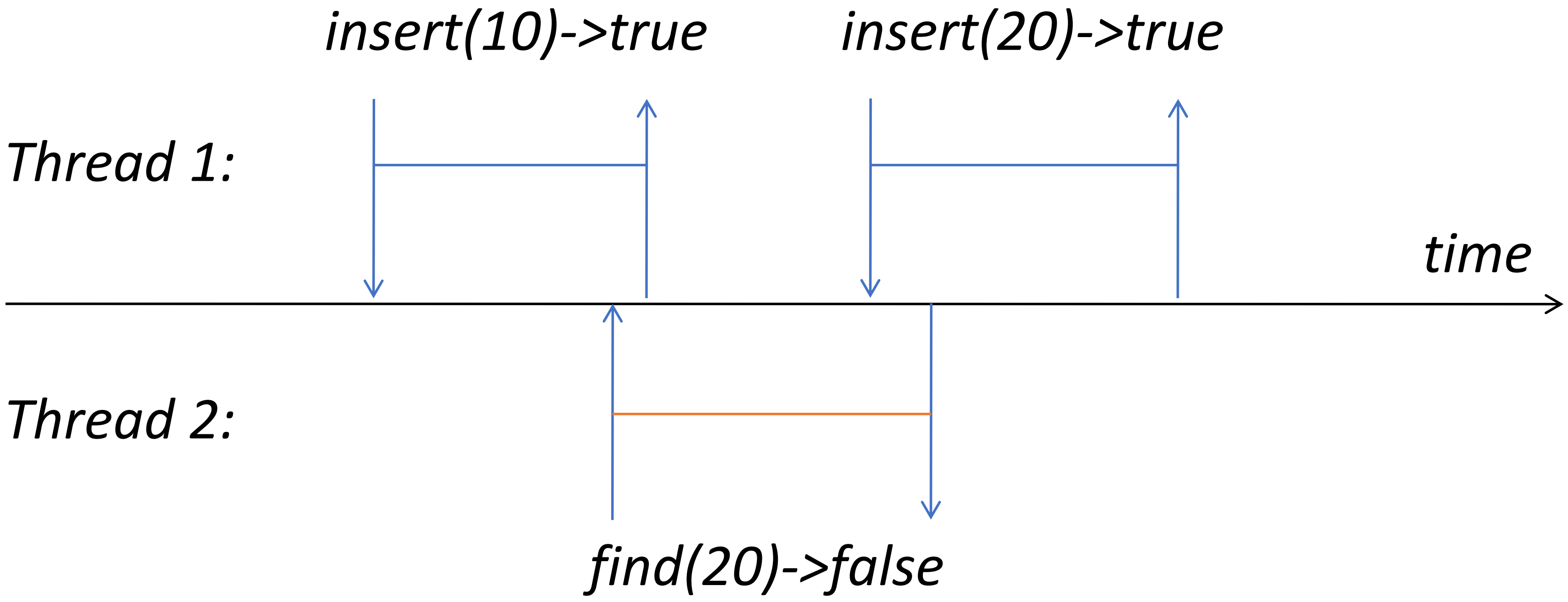
Why is this one OK?

Total Order:

1. Insert(10)
2. Find(20)
3. Insert(20)

- Is consistent with real-time order
- 2, 3 overlap, but return order OK

Example: linearizable



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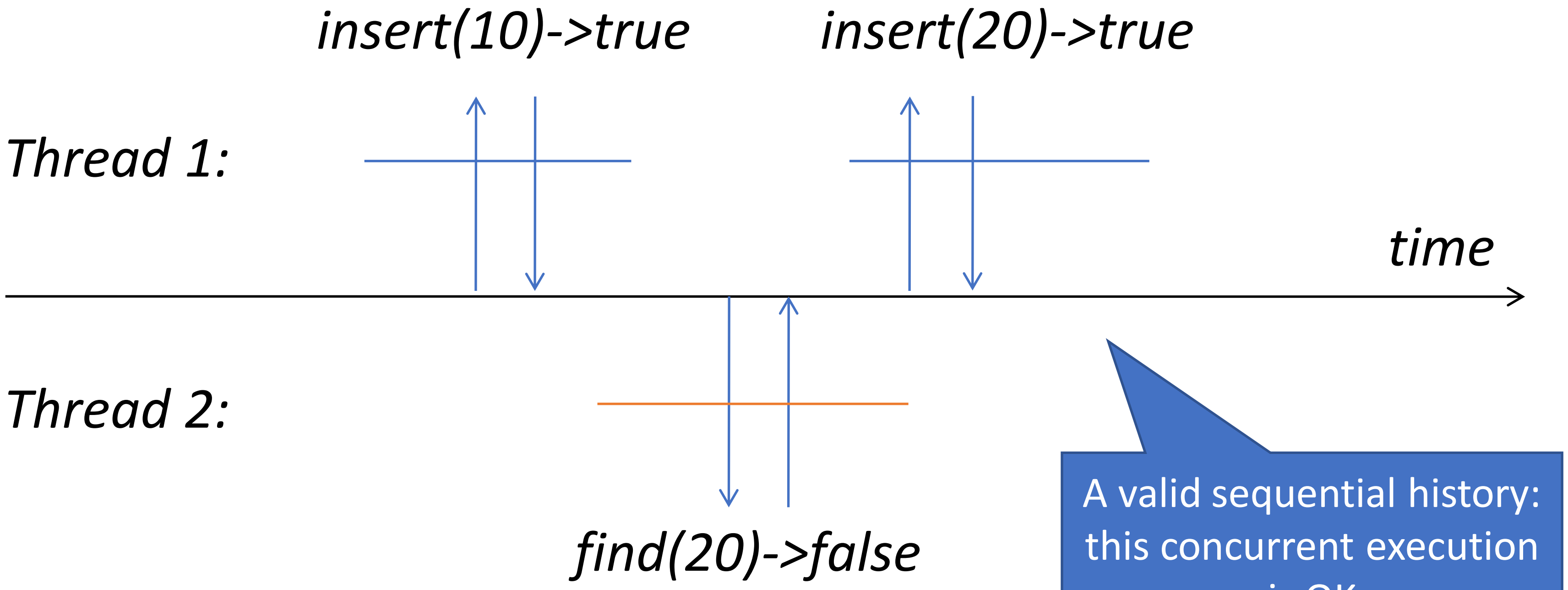
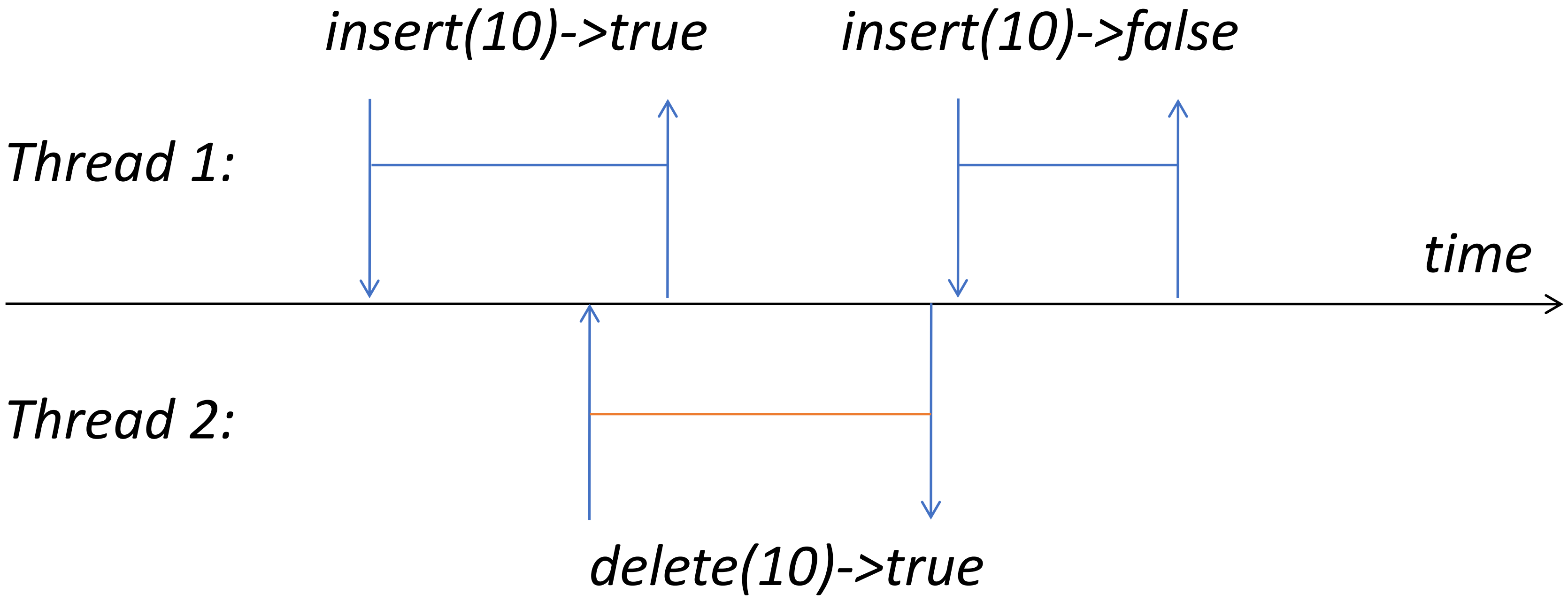


A valid sequential history: this concurrent execution is OK

Note: linearization point

Example: not linearizable



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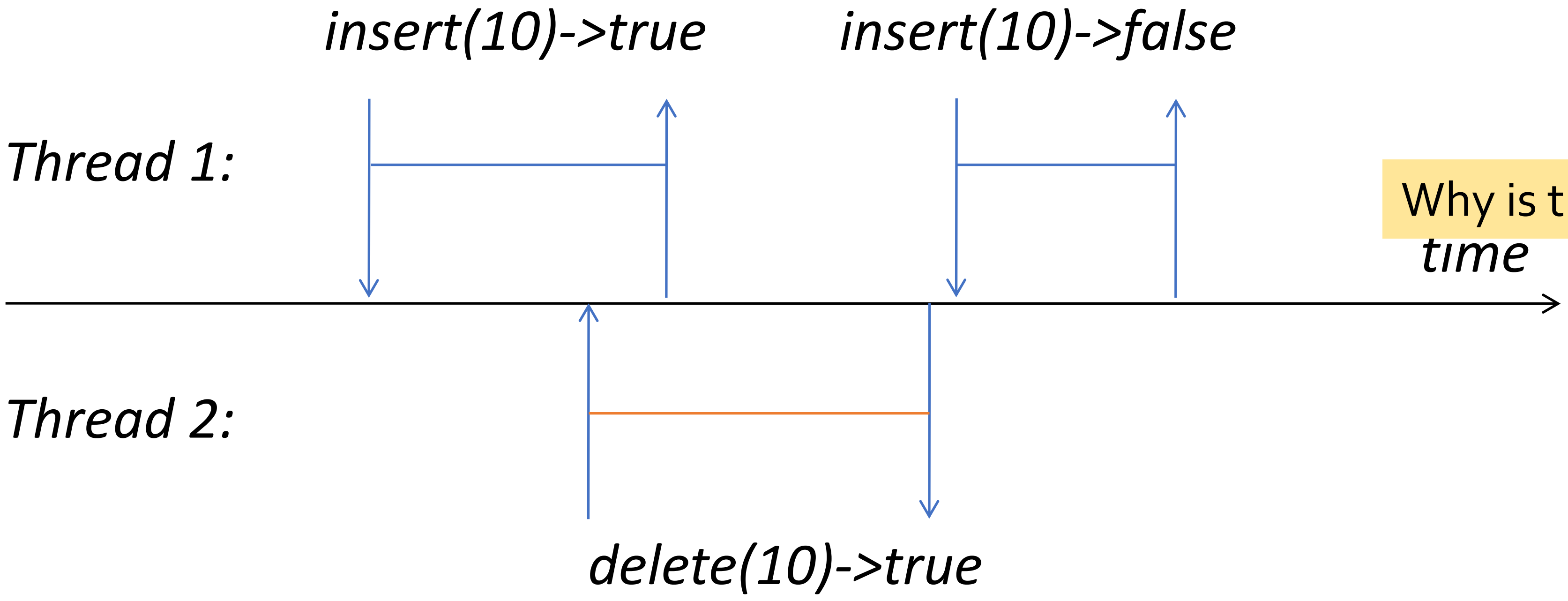

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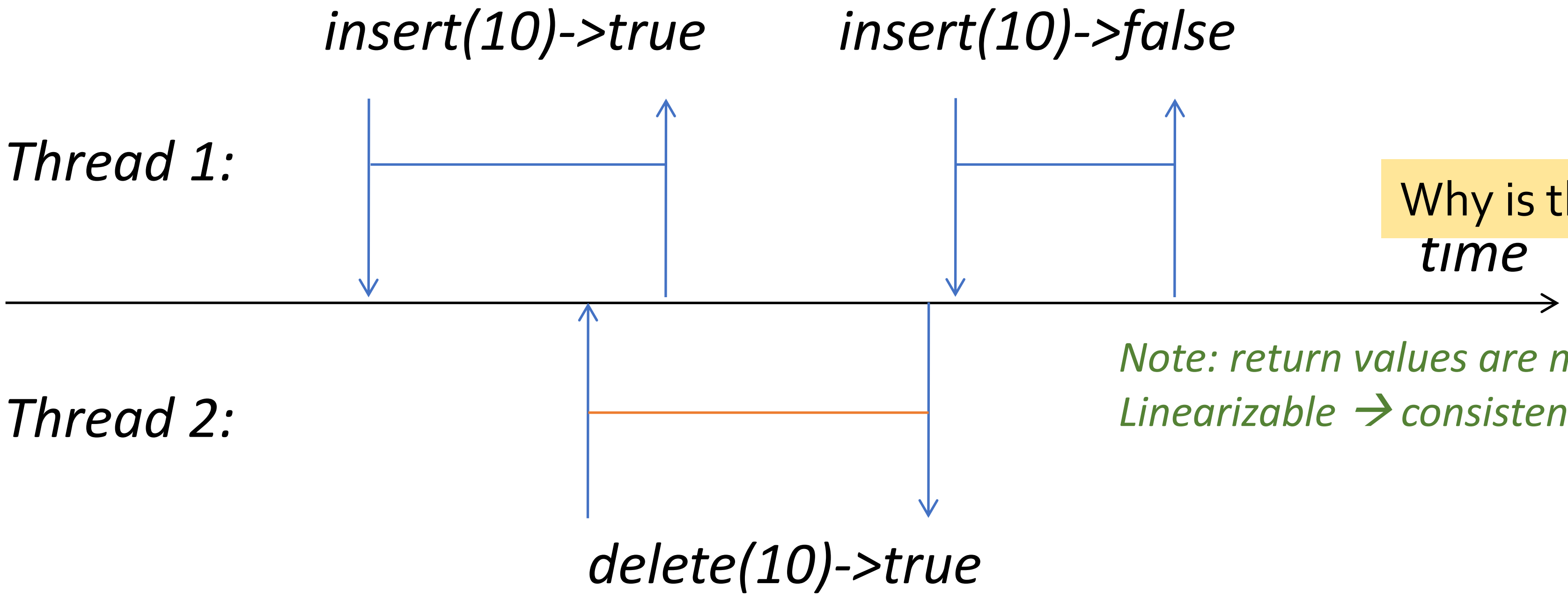

Why is this one NOT OK?

Note: return values are meaningful!

Linearizable → consistent with return values

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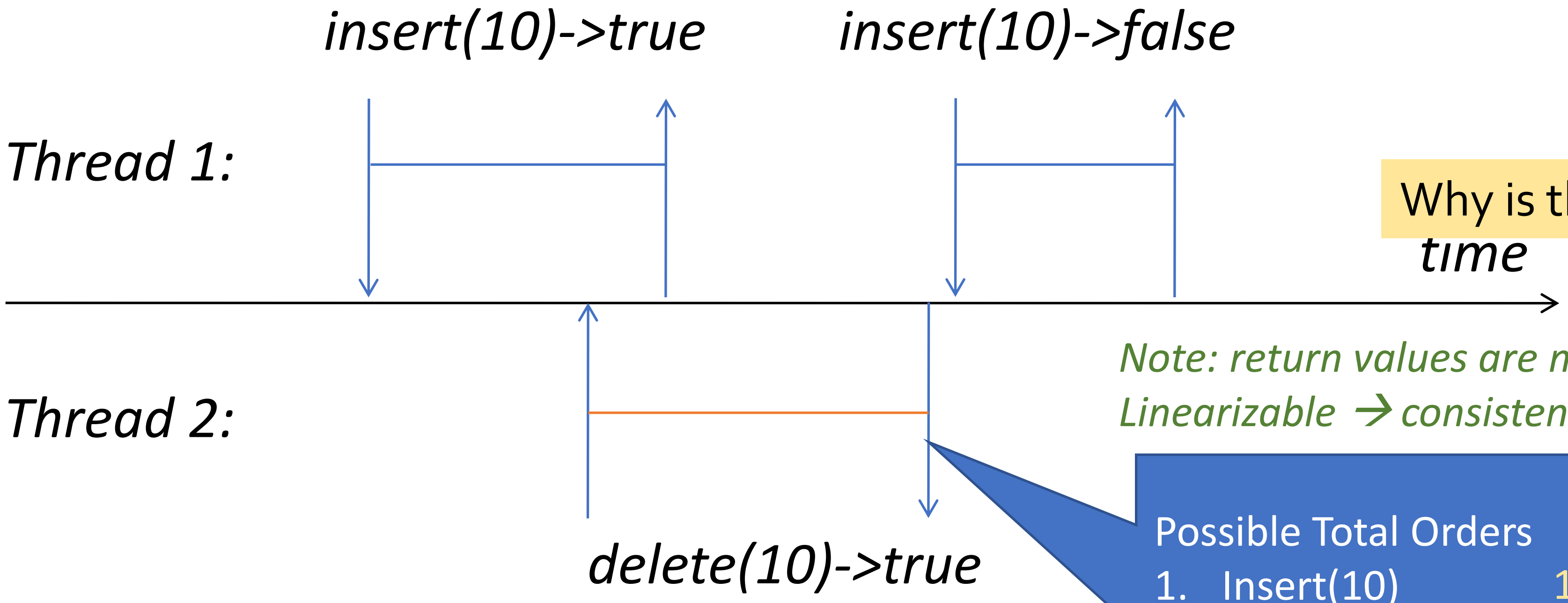

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Possible Total Orders

1. Insert(10)	1. Delete(10)
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- Both consistent with real-time order
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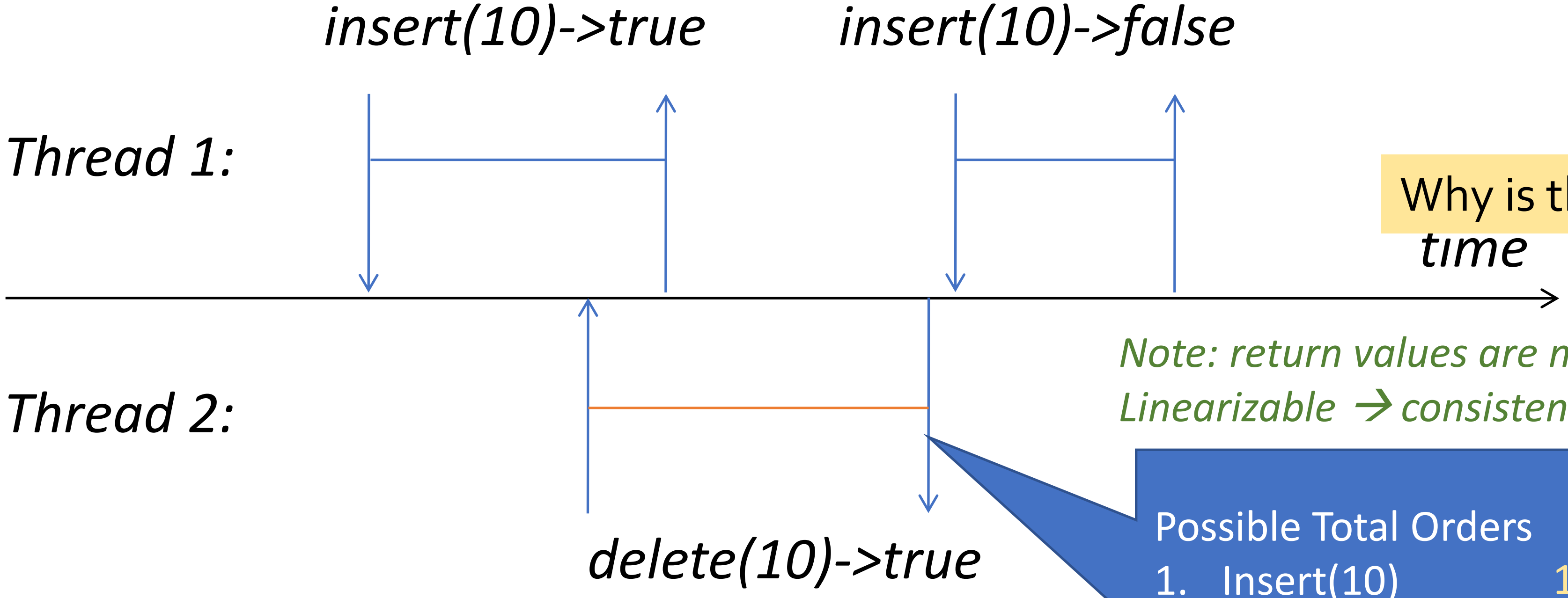

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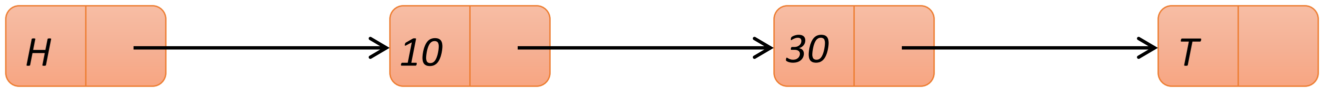
How can things like this happen?

Example Revisited

- find(20)



Thread 1:

Thread 2:

Example Revisited

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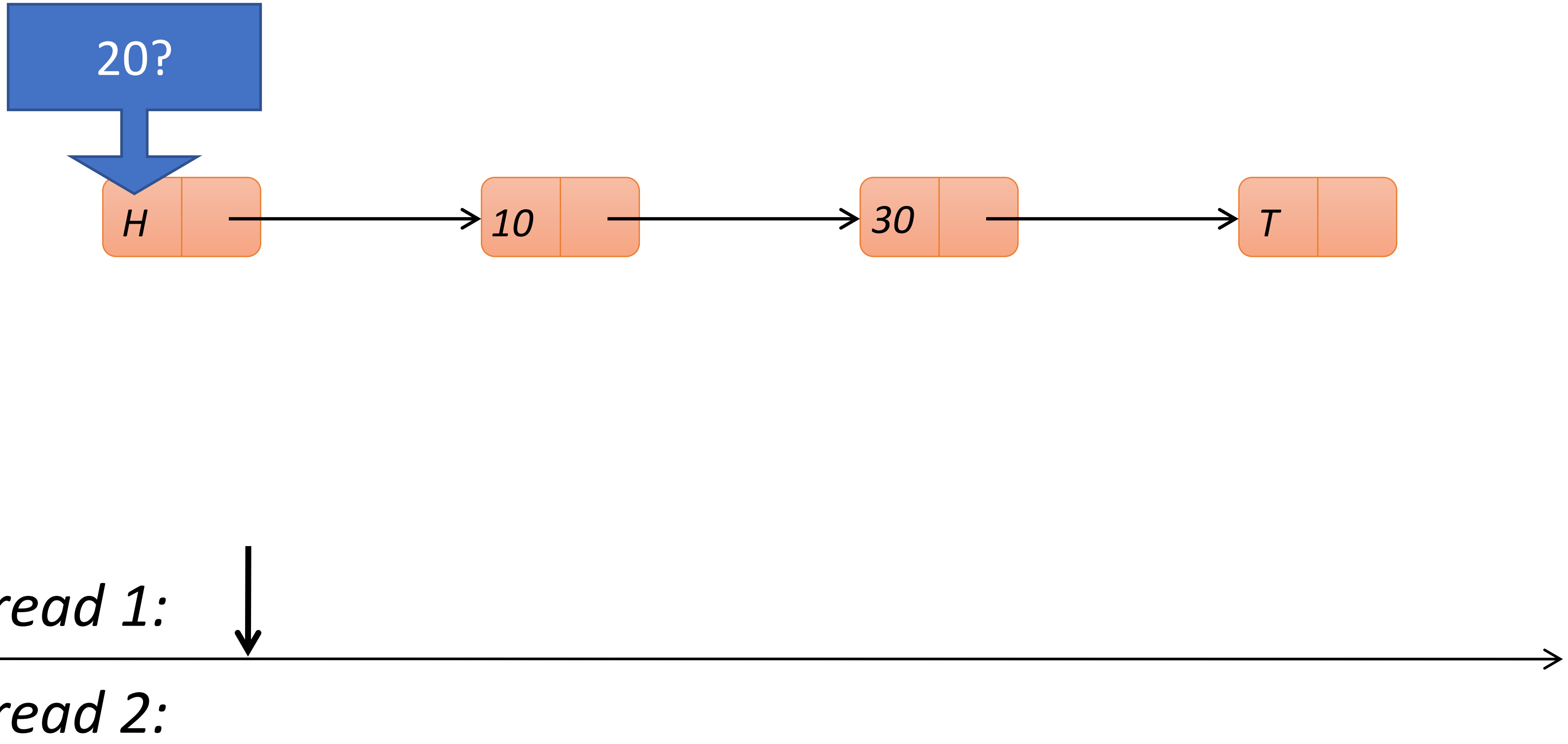

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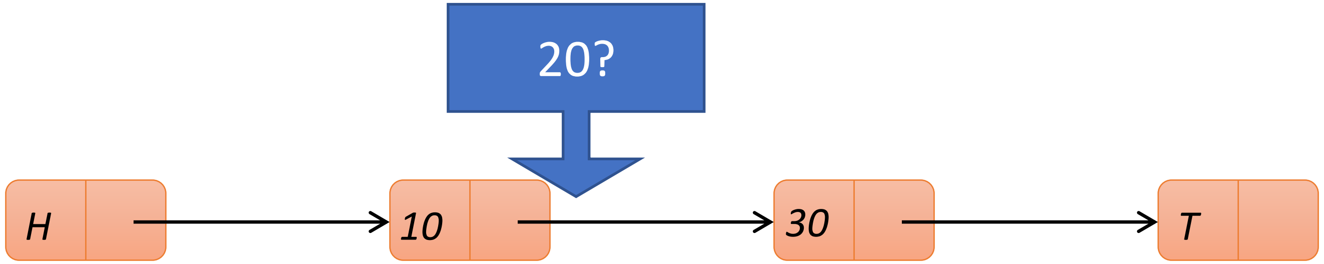

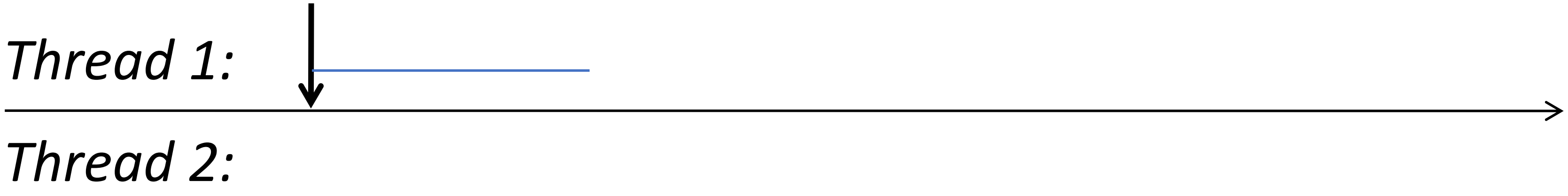

Example Revisited

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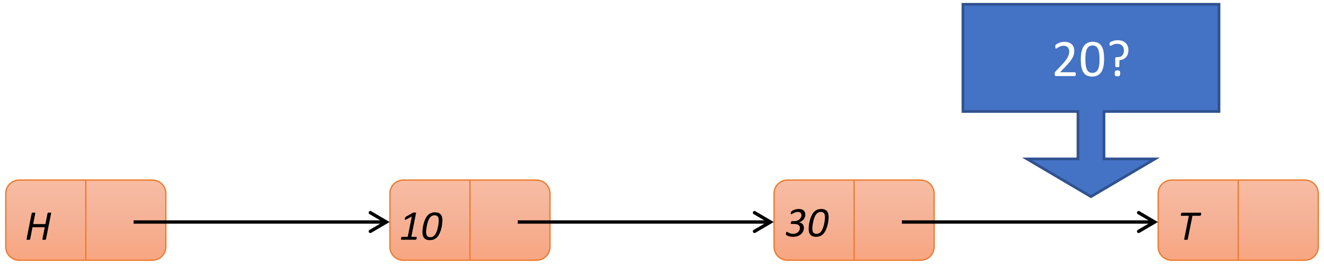

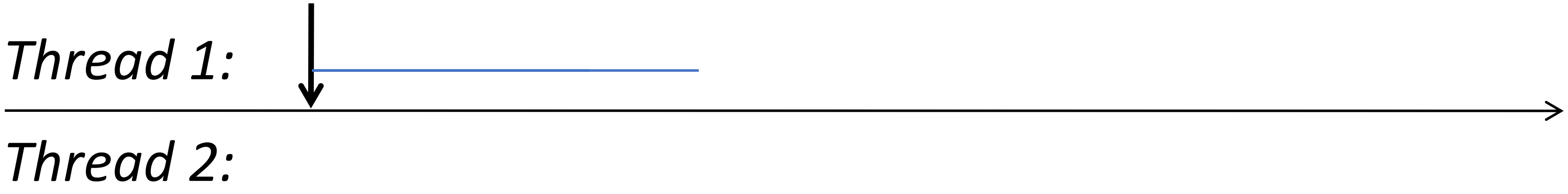

Example Revisited

- find(20)
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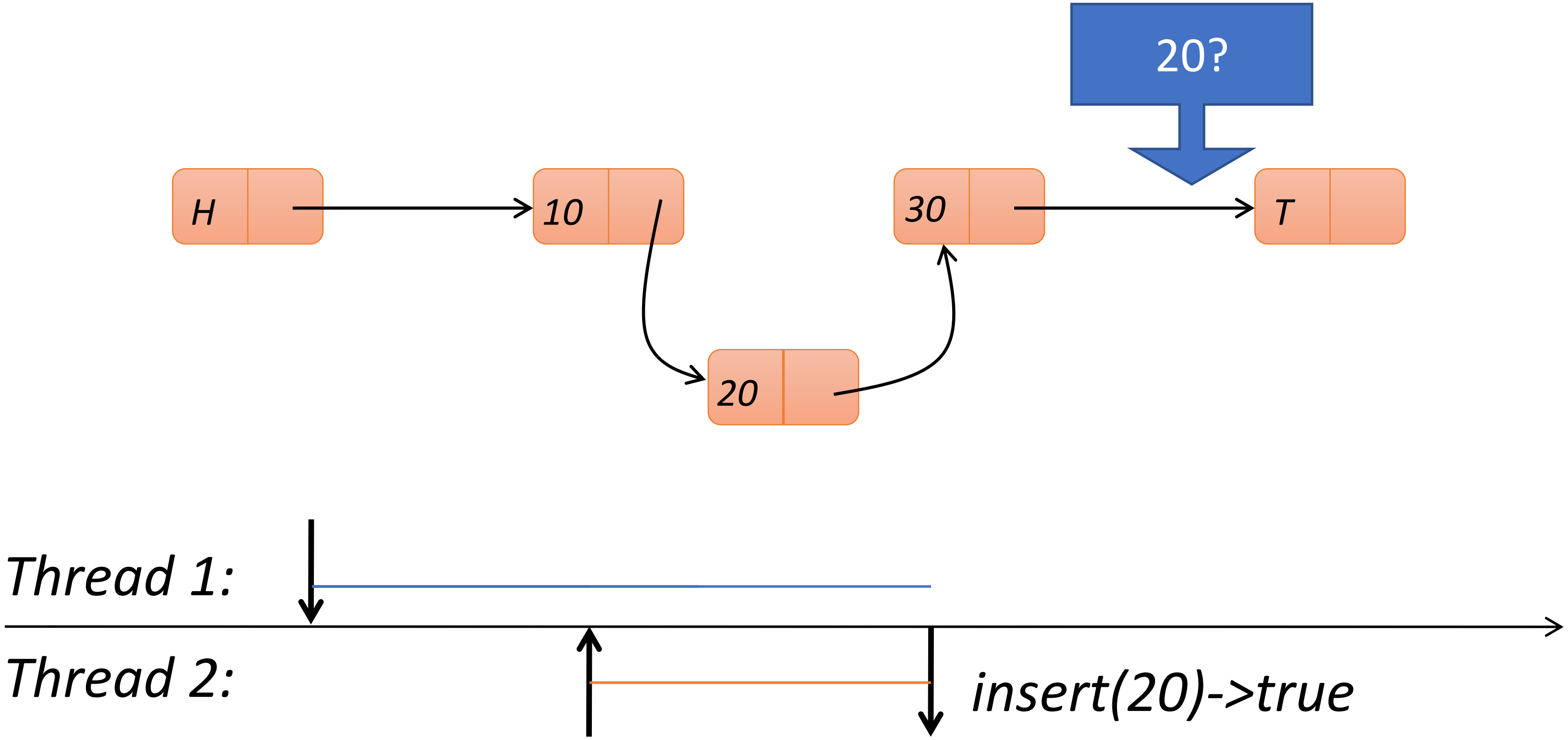

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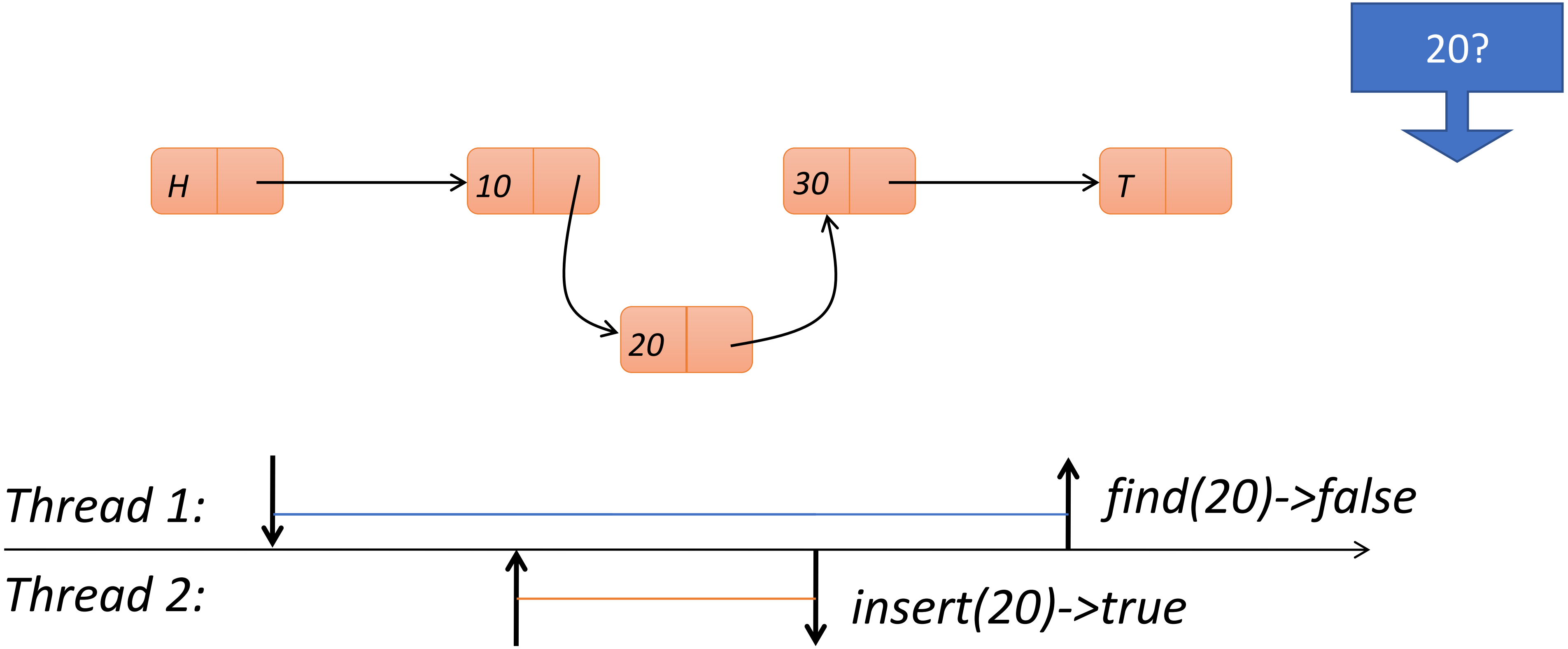

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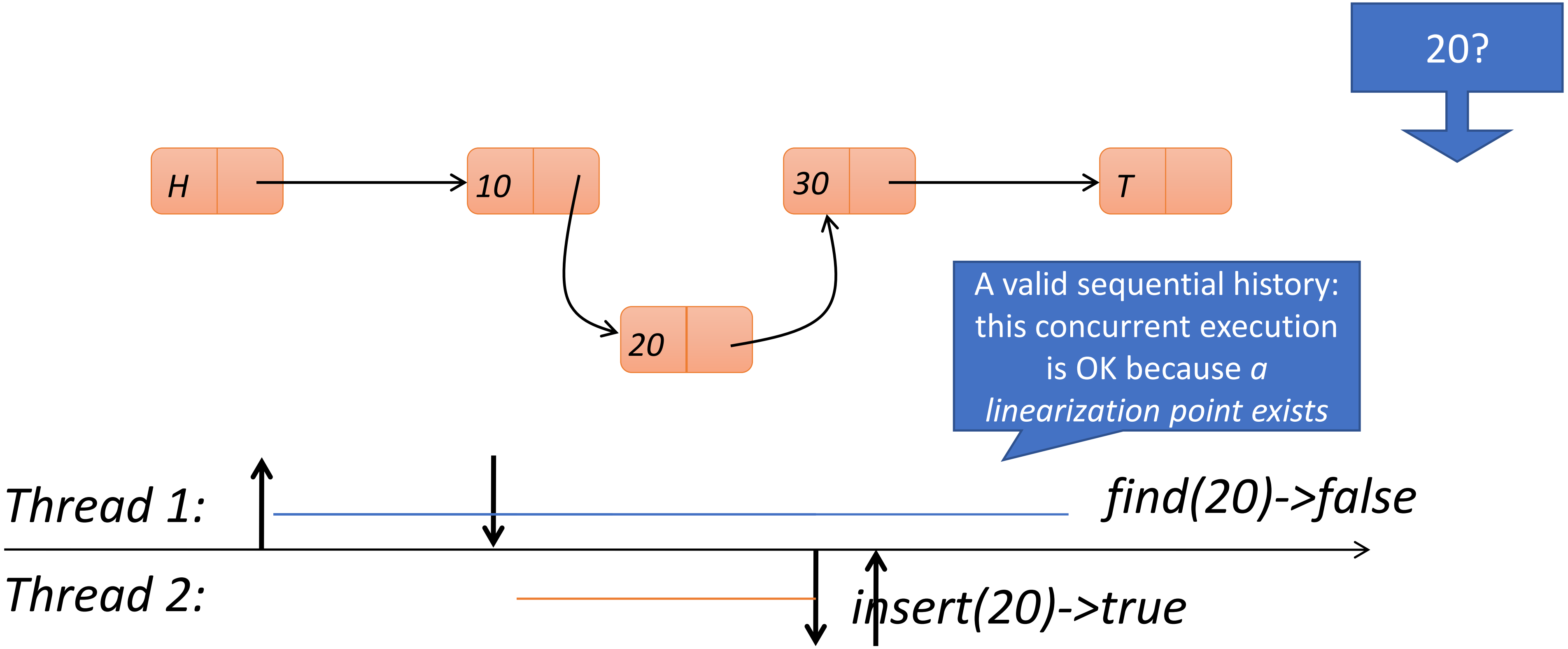

A valid sequential history: this concurrent execution is OK because *a linearization point exists*

Example Revisited

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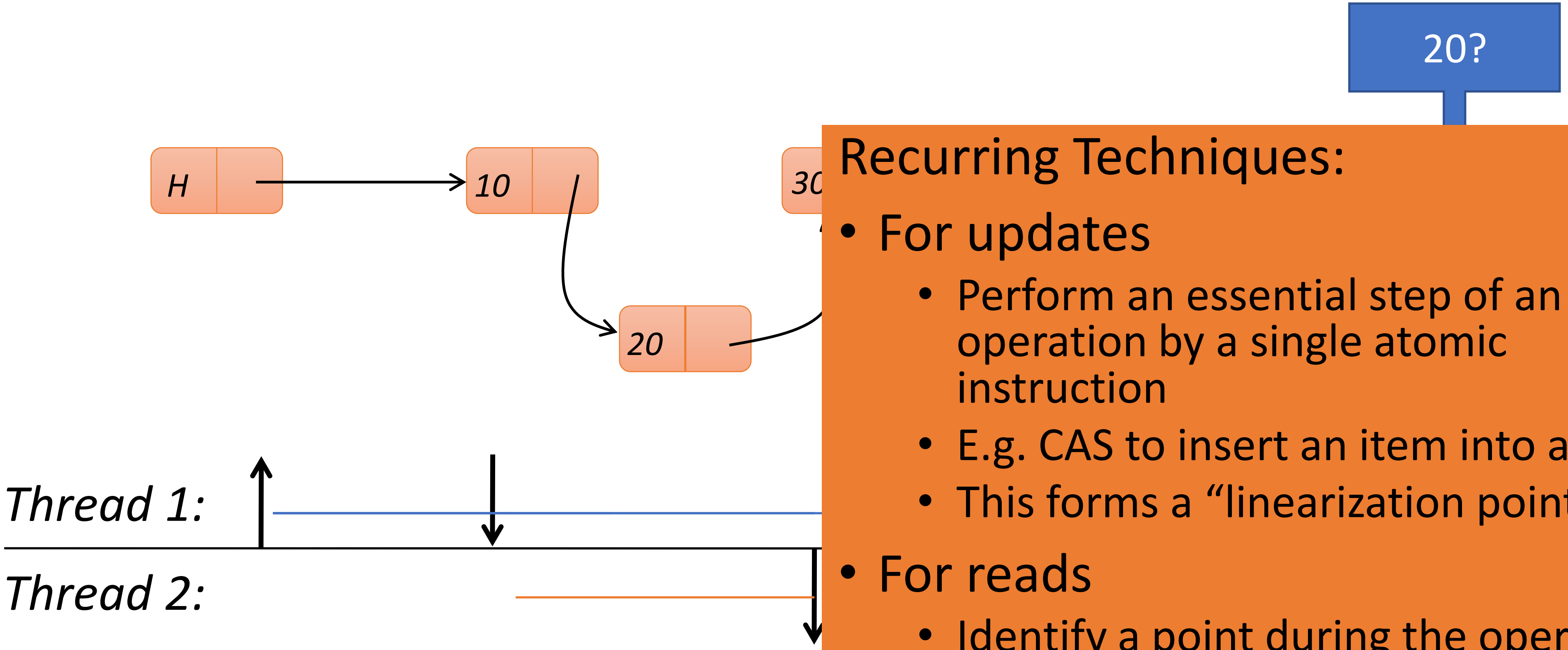

Recurring Techniques:

- For updates
  - Perform an essential step of an operation by a single atomic instruction
  - E.g. CAS to insert an item into a list
  - This forms a “linearization point”
- For reads
  - Identify a point during the operation’s execution when the result is valid
  - Not always a specific instruction

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- Obstruction-free
  - A thread finishes its own operation if it runs in isolation
  - Very weak. Means if you remove contention, someone finishes

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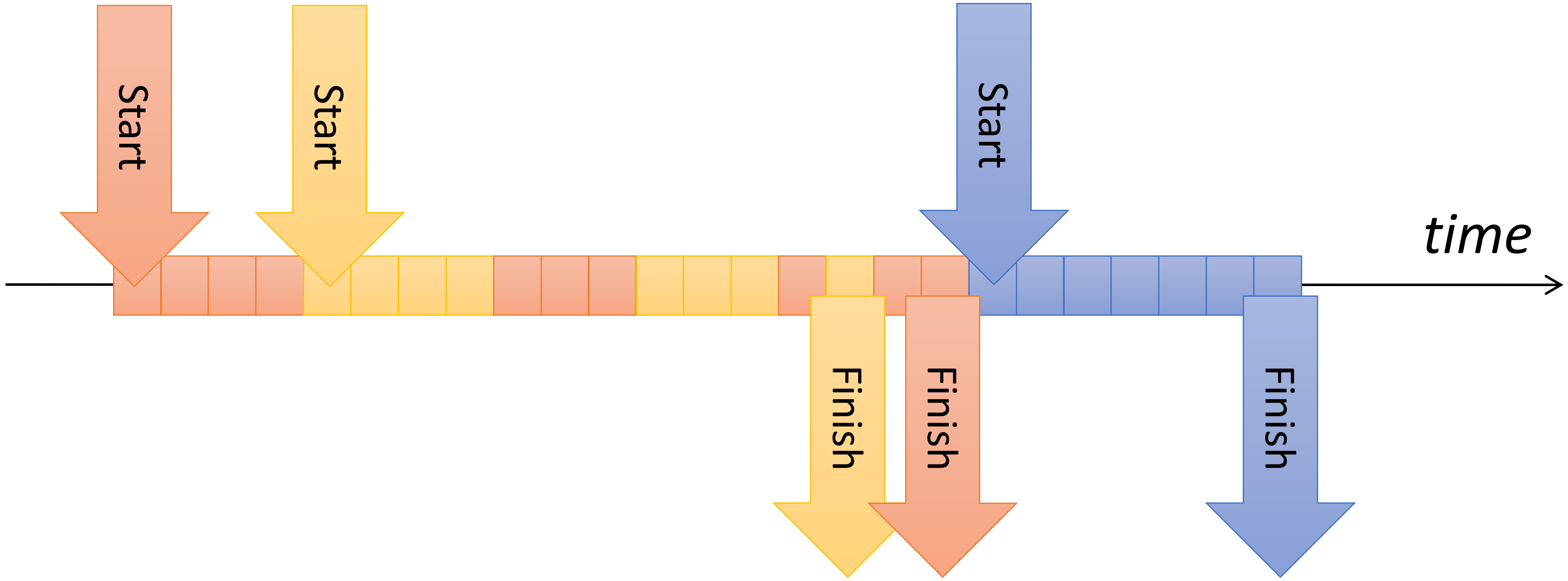

Lock-free

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Lock-free

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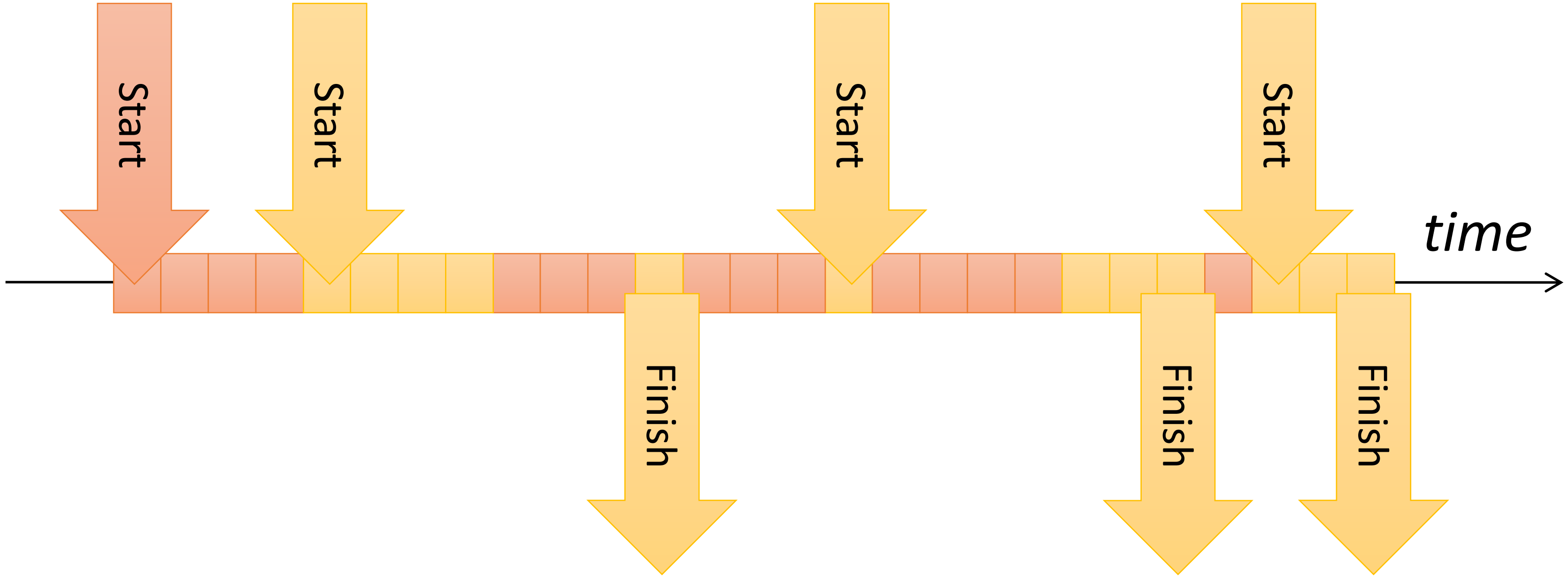

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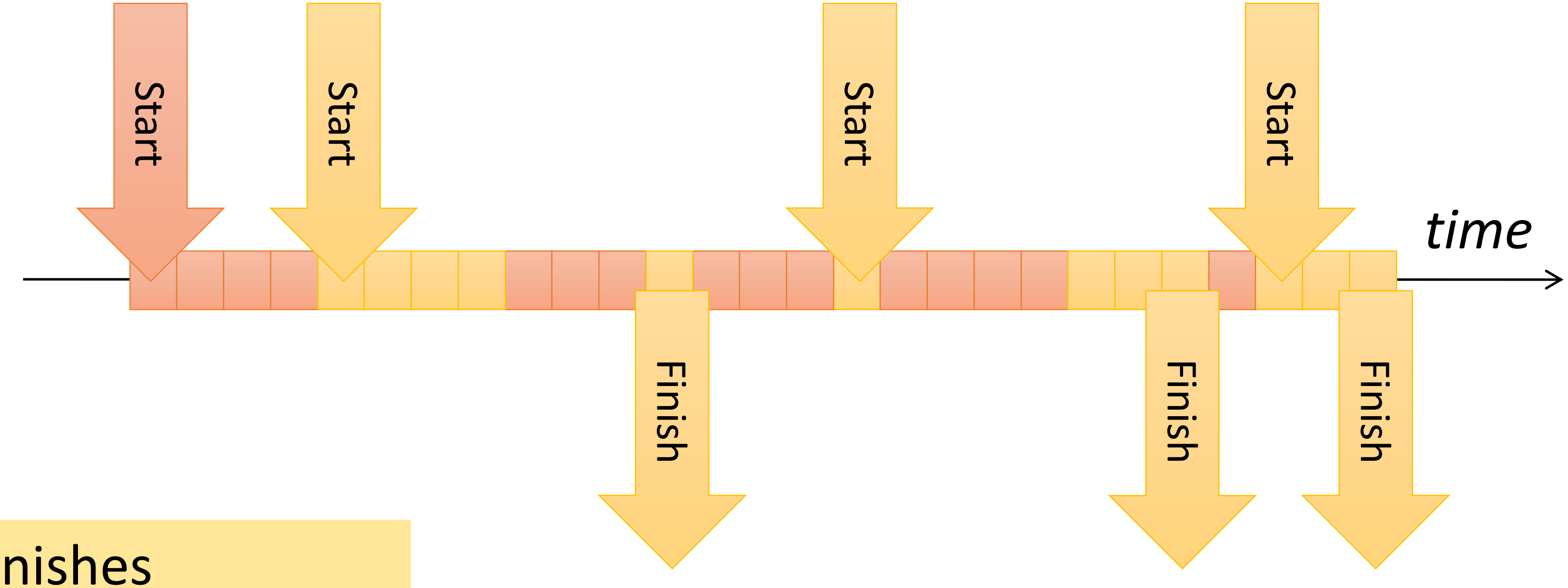

- Red never finishes
- Orange does
- Still lock-free

Obstruction-free

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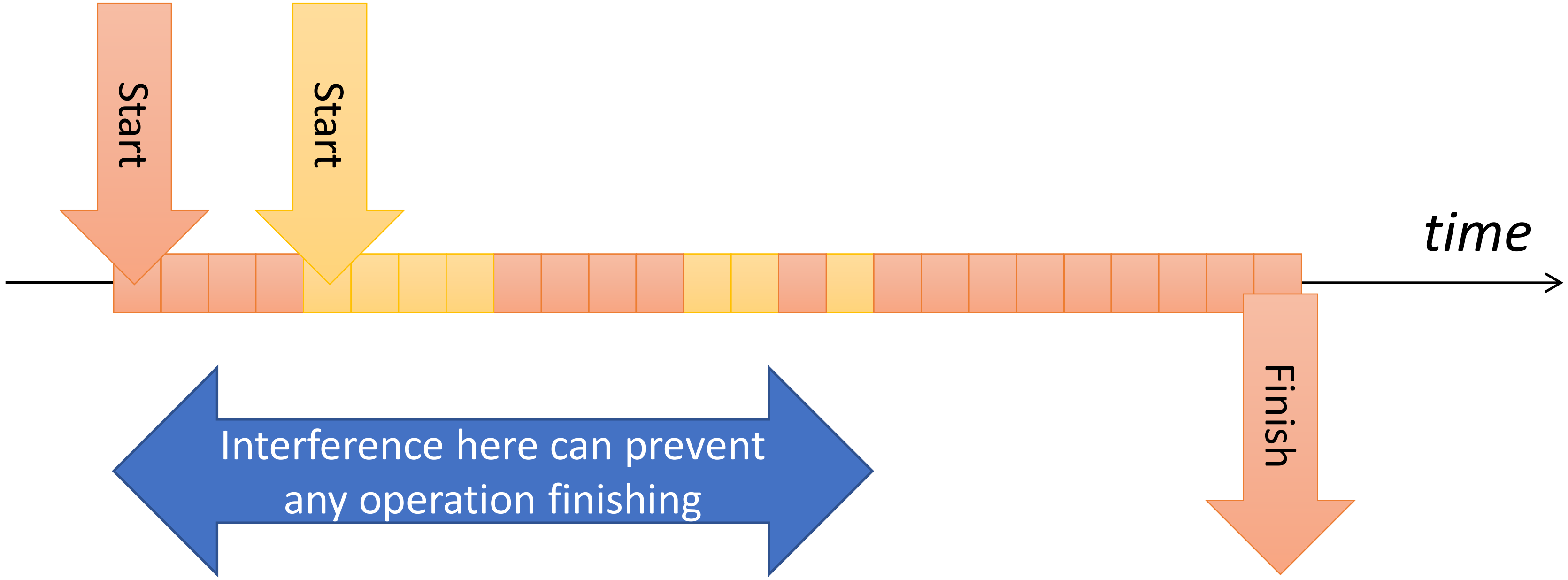

Formal Properties

- Wait-free
  - A thread finishes its own operation if it continues executing steps
  - Strong: everyone eventually finishes
- Lock-free
  - Some thread finishes its operation if threads continue taking steps
  - Weaker: some forward progress guaranateed, but admits unfairness, live-lock, etc.
- Obstruction-free
  - A thread finishes its own operation if it runs in isolation
  - Very weak. Means if you remove contention, someone finishes

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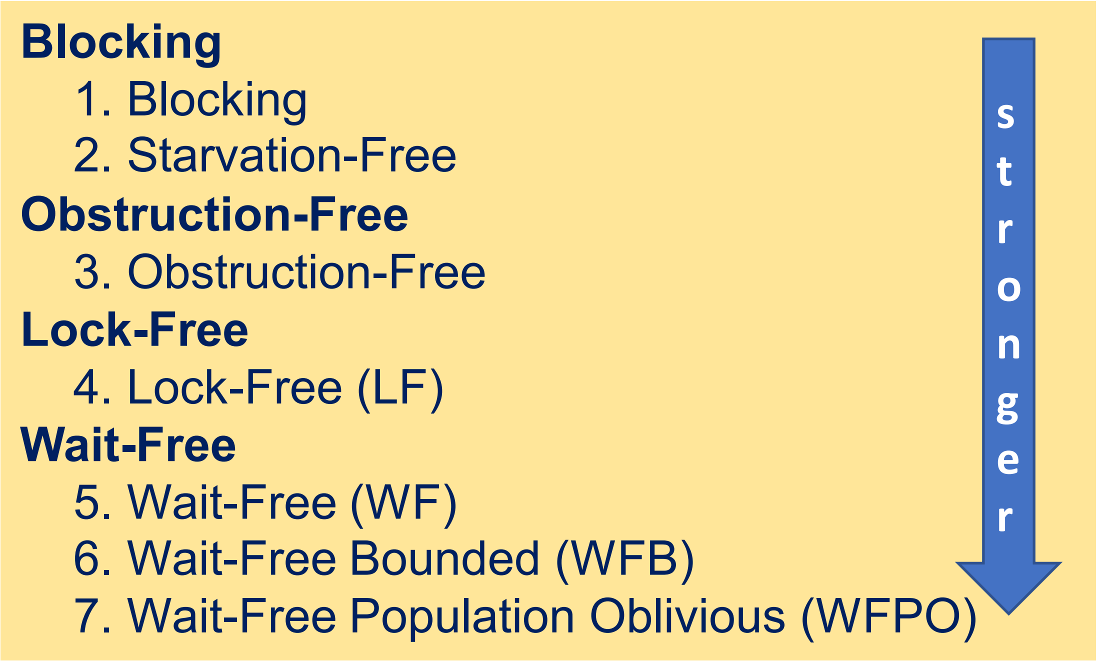

Blocking

1. Blocking
2. Starvation-Free

Obstruction-Free

3. Obstruction-Free

Lock-Free

4. Lock-Free (LF)

Wait-Free

5. Wait-Free (WF)
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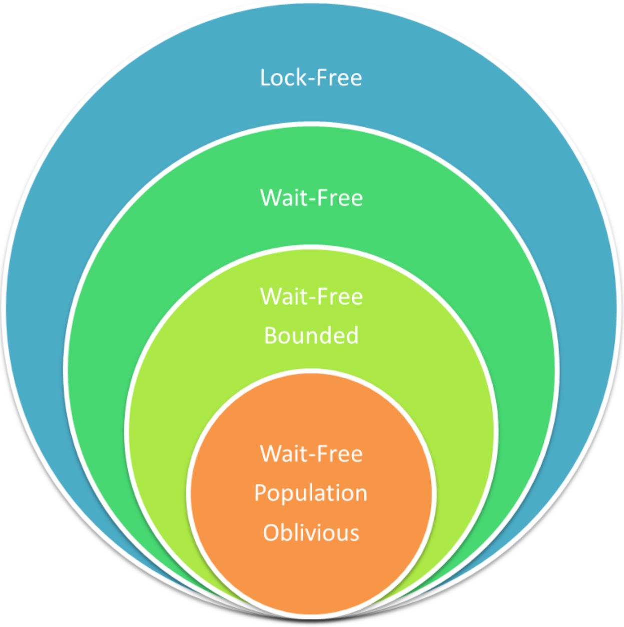

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Huh? Composable?

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Thread-safe?

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- Lock-based code doesn’t compose
- If list were a linearizable concurrent data structure, composition OK

Linearizability Properties

- non-blocking
  - one method is never forced to wait to sync with another.
- local property:
  - a system is linearizable iff each individual object is linearizable.
  - gives us **composability**.
- Why is it important?
  - Serializability is not composable.
  - Core hypotheses:
    - structuring all as concurrent objects buys composability
    - structuring all as concurrent objects is tractable/possible

Practical difficulties:

- Key-value mapping
- Population count
- Iteration
- Resizing the bucket array

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Options to consider when implementing a “difficult” operation:

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Fall back to a simple implementation if permitted
(e.g., lock the whole table for resize)

Design a clever implementation
(e.g., split-ordered lists)

Use a different data structure
(e.g., skip lists)